ENVIRONMENTAL IMPACTS ON GUAM'S WATER SECURITY AND SUSTAINABLE MANAGEMENT OF THE RESOURCE

By

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A Dissertation Submittal in Partial Fulfilment of the Requirements

For the Degree of

Doctor of Philosophy

in

Environmental Studies and Water Security

University of Alaska Fairbanks

May 2018

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Abstract

Impacts of climate change on the already severely strained freshwater resources of approximately 1000 inhabited islands in the Pacific Ocean are of great concern. The Western Pacific region is one of the world's most vulnerable when it comes to risk of disaster particularly for the several of the low-lying coral islands. Impacts have already been felt regarding the security of water resources that would directly impact agriculture, forestry, tourism and other industry-related sectors. The ironic and tragic aspect of the environmental crisis of greenhouse emissions is the fact that those parts of the world least responsible for creating the water security issues are the first to suffer its consequences. Pacific Island Nations are responsible for only 0.03 percent of the world's carbon dioxide emissions, and the average island resident produces only one-quarter of the emissions of the average person worldwide.

Utilizing the historical data, the evidence of change in water quality and access on Guam has been examined. All indicators except for the precipitation support the hypotheses that climate change trends are impacting Guam's water security. This will eventually weaken Guam's resilience. As a result of this research and its recommendations, a sustainable freshwater resources management plan, for a water-secured Guam can be produced. Adaptive management provided here is based on a process that can measure the resilience of Guam to the issue of water security.

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Acknowledgments

This research is the result of my work and the work done by others compiled in such manner that has hopefully responded to the research questions leading to conclusions and recommendations related to sustainable water resources management for the Island of Guam. The author wishes to express his sincere appreciation for the wealth of data collected from sources such as; National Oceanic and Atmospheric Administration (NOAA, U.S. Department of Commerce), Guam Waterworks Authority (GWA), Federal Environmental Protection Agency Region IX, Water and Environmental Research Institute of the Western Pacific (WERI) and its respective researchers and faculty, University of Guam, and several papers, reports, chronicles and published materials by scientists who without their contribution this work would not have become a reality. Special thanks is extended to the University of Alaska, Fairbanks and its dedicated faculty including Dr. Lawrence L. Duffy (research committee chair) who lifted my spirit with his kindness when I was downhearted and taught me so much about Environmental Chemistry, Dr. Barbara Adams as my general mentor in this Journey who taught me research methods and made the science of statistics fun, Dr. David Barnes, P.E. who offered his brilliant environmental and civil engineering ideas about this research, Dr. Alicia Aguon (my Co-chair) who without her support achieving my degree in the higher education would have been impossible, Dr. Salman Taghizadegan who kept me inspired and showed me the path. Dr. Troy McVey, my PhD. Cohort members (UOG-UAF Cohort No. 1) specifically Mr. Manny Hechanova for his continuous technical support. I would like to thank the University of Alaska Fairbanks Administrative support including Ms. Shelly Baumann, Ms. Jessica Armstrong, Ms. Mary Van Muelken, Ms. Megan Blanchard, Ms. Gretchen Hundertmark, Ms. Mandi Goddard, Ms. Laura Bender, and especially Dr. Allan A. Morotti, for the heartfelt support and guidance.

Dedication

To: my wife Alieh, my daughter Shawdee, my son Ashkan, my mother Shamsy, my father Amir, and my sister Mina for their patience, love, and support.

Chapter 1 Introduction and Literature Review

Water is a vital feature that makes Earth a hospitable place to live. Water, H_2O, a molecule with a deceptively simple formula, but one with remarkably complex properties is a medium in which life can exist. Without it, all cell biochemical reactions, respiration, and photosynthesis, the very process of life, will cease to exist. As we deal with the sustainability challenge of preserving this resource, it is essential to know about water, its properties, where it comes from, how it is used, how it is purified, and how it may be treated to keep it pure. Properly used, water is nature's most sustainable and renewable resource. (Manahan 2010)

Water Security has been defined as the reliable availability of an acceptable quantity and quality of water for health, livelihoods and production. Sustainable development will not be achieved without a water secure world. A water secure world leads to survival of all living species, and human well-being to include adequate standards of food and goods production, proper sanitation, and sustainable healthcare. Water security allows harnessing water's productive power and minimizes its destructive force. Water security also means addressing contamination from human activity, environmental protection and the negative effects of poor management. A water secure world improves living standards.

Some of the countries and regions suffering most from water security issues are North Africa, the Middle East, India, Central Asia, China, Chile, Colombia, South Africa and Australia. Water scarcity issues are also increasing in South Asia, and in the Pacific Island Nations. The small island communities of Oceania have numerous problems and few resources to address water security issues.

The territories depend on the governing states to be responsible, and the independent island states generally do not have the resources or capacity to address the water related problems on their own. The Oceania region includes more than 20,000 islands (Sirgy et al. 2017)

Air and maritime links between the island countries and the rest of the world are, at best, not well developed, and at worst they hardly exist. Some countries are as small as 21 square kilometers (For comparison, the United States is nearly 10 million square kilometers). The island states range in population from the 7.4 million people living in Papua New Guinea to the 10,000 people living in Nauru or Tuvalu. Per capita gross domestic product across the region ranges between about USD $2,000 to $5,000. The Pacific islands are mostly out of sight and mind for the rest of the world. To the extent that the region does come to mind, it is not listened to regarding current issues such as climate change and the rise of sea-levels.

As a result of the challenging circumstances of sea level rise, the Pacific islands primarily face issues of human security, including high mortality rates, health deficiencies, individual poverty, and the inability to develop their economies. They are hampered by foreign states from exploiting their natural resources such as minerals, timber, and fisheries. Since climate change creates the imminent threat of rising air, surface water temperatures, sea-levels, plus frequent storms with higher intensity and long duration of precipitation, Guam faces the reduction of available land and the destruction of fresh water supplies that can directly impact its water security among other issues.

Over the past 150 years, anthropogenic global activities have increased the atmospheric concentration of carbon dioxide (CO_2) by 39 percent and (CH_4) has more than doubled. Increasing methane emissions are primarily from intensive livestock farming and fossil fuel production (Leung et al. 2014).

In order to better realize the gravity of global warming and its potential impacts on a small Pacific Island, a summary result of Intergovernmental Panel on Climate Change (IPCC) following Representative Concentration Pathway (RCP) Scenario 8.5 as the highest projected level of future greenhouse gas emissions model is provided in Table 1.1 (Collins et al. 2013). This is a modified table where the most immediate future goals are presented, categorized as research, infrastructure and social capital. These recommendations are associated with and related to air temperature, sea level, extreme events and storm surge, and precipitation.

Table 1.1 Summary Result of Climatological Model Global and Coarse End-of-Century Projections for Select Climate Indicator Variables using the IPCC's RCP8.5 Scenario (the highest projected level of future greenhouse gas emissions).

Climate Indicator	Year	Projection
Mean Annual Air Temperature	2050–2074 (compared to 1980–2004)	Increase of 1.99°C over the average
Mean Daily and Annual Precipitation	2050–2074 (compared to 1980–2004)	Moderate increase of 0.61 mm/day (.03 in/day) (222.2 mm/year; 8.7 in/year) over the average
Global Mean Sea Level	2046–2065 (compared to 1986–2005) 2081–2100	An increase of 0.30m (0.22–0.38m) An increase of 0.74m (0.52–0.98m)
Mean Annual Extreme Events	End of 21st century	Fewer, more intense storms with changing track location (potentially moving poleward)[6].

The concentrations of other greenhouse gases have increased. The climate of the world has initiated its response.

- Global average temperature has risen about 0.8°C (1.4°F) since 1850.
- Minimum summer sea ice extent in the Arctic has decreased about 21 percent since 1979.

- Mountain glaciers, the Greenland and Antarctic ice sheets have started to lose mass.
- Sea level has risen by about 0.2 m (0.7 ft), and the rate of rise in the early 21st century is approximately double the average rate for the 20th century.
- Both the broad mid-latitudinal bands of precipitation and the dry subtropical bands have started shifting poleward.

When viewed as global averages, where changes seem to occur slowly, the impression is that climate change is likely to proceed in a slow, steady fashion. This impression leads to a common presumption that there will be ample time to prepare for climate change and its associated impacts.

Scientists typically average climate variables (e.g., temperature or precipitation) over long time periods (~30 years) and over large regions so that reported climatic conditions will appear to change slowly. The actual impacts may be more sudden and more concentrated in particular locations. For example, storms, that often have local impacts, already appear to become more intense. (MacCracken and Richardson 2010)

Around the world, observations indicate that a larger fraction of rainfall activity is in the form of downpours. Downpours tend to increase the rate of runoff that fills streams and rivers rapidly. When falling on snowpack, heavy downpours increase their melting rate.
Such episodes increase the likelihood of flooding. An increasing fraction of tropical storms (i.e. hurricanes, cyclones, and typhoons) are intensifying toward the most powerful categories 3, 4 and 5. As seen during recent 2017 storm events, such as Hurricanes Arlene, Bret, Cindy, Don, Emily, Franklin, Gert, Harvey, Irma, Jose, Katia, Lee, Maria, Nate, Ophelia, Phillipe, Rina, Sean, Tammy, Vince, and Whiney have broken historical records in several categories.

For example, it is noteworthy that during passage of Hurricane Harvey (August 2017) over the landmass, rainfall occurred with an exceedance frequency resembling a 500-year storm.

Higher and stronger storm surges will cause greater damage and more frequent coastal inundation. Sea level rise means that less intense storms can also lead to inundation. Day-to-day variations in the weather about the long-term average are generally distributed in the shape of the familiar bell curve. For example, average daily high temperatures for a given month tend to be distributed in this way, with the peak representing the average daily high temperature for that month and the width of the bell curve representing the degree of variation. As the climate changes, both characteristics tend to shift toward higher values, increasing both high and low extremes. The following figures illustrate this point and are provided courtesy of the proceedings of the National Academy of Sciences of the United States, September 11, 2012 Volume 109-No. 37, (Hansen et al. 2012)

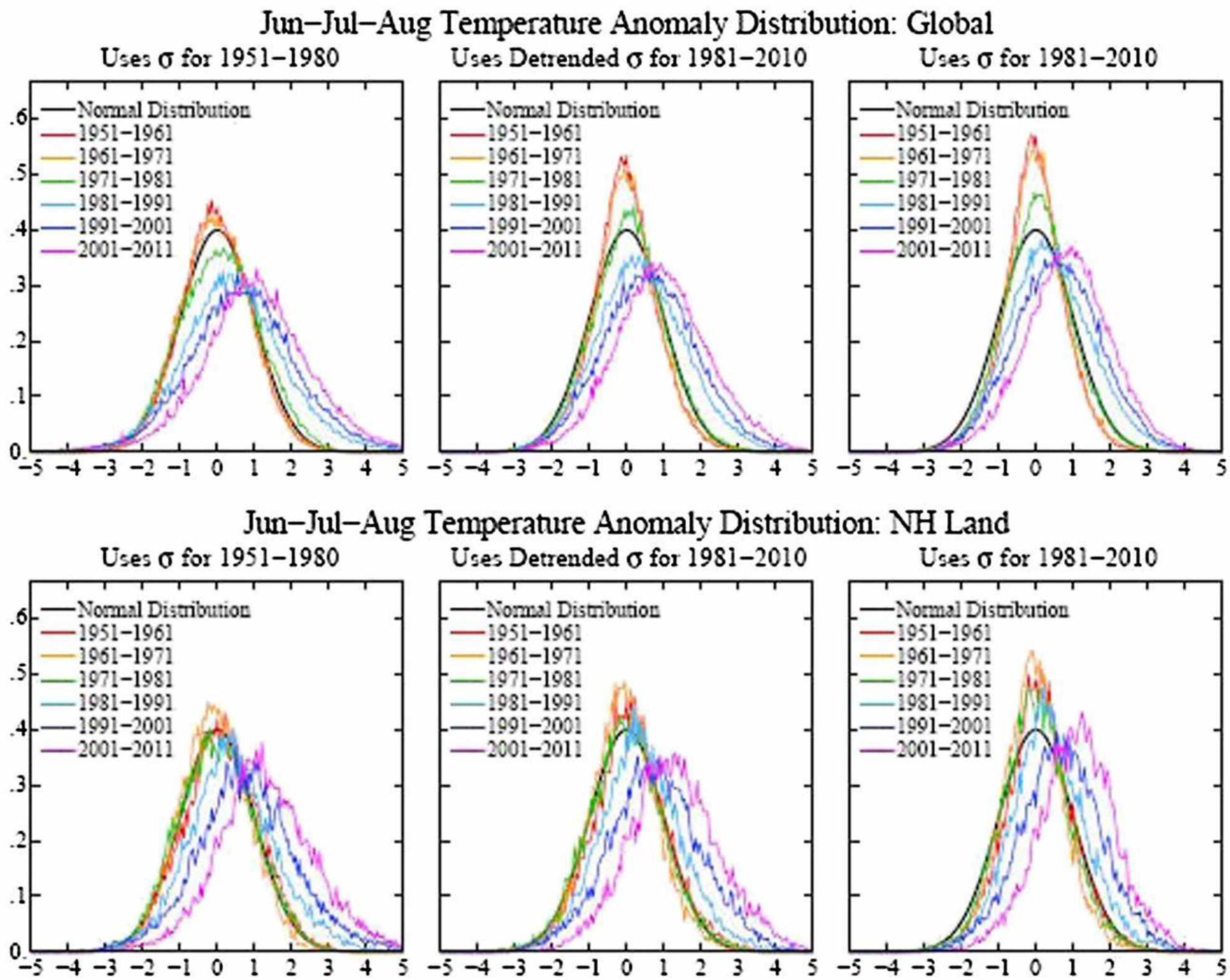


Figure 1.1 Perception of Climate Change, Frequency of occurrence (y axis) of local temperature anomalies (relative to 1951–1980 mean) divided by local standard deviation (x axis) obtained by counting grid boxes with anomalies in each 0.05 interval. Area under each curve is unity.

Presently, some drainage structures are designed and constructed to withstand one-in-a-hundred-year floods based on the previously appropriate historical records. As climate change shifts the statistical envelope that bounds the intensity, range, scale, and duration of weather extremes, intense events that can cause significant damage are projected to become much more likely. The result is that large areas are likely to be more frequently exposed to conditions that exceed existing tolerance thresholds.

As the statistical data become less reliable, higher factors of safety should be considered in designing infrastructure and building facilities that are costlier to construct and will directly impact resources for building material.

In other coastal regions around the world, longer intervals between significant rains are leading to prolonged periods with increased evaporation and therefore more periods of drought (MacCracken and Richardson 2010)

In addition to agricultural losses and disrupted water supplies, one consequence of prolonged dryness is an increase in the frequency and intensity of wildfire. Wildfire causes loss of ground cover that leads to erosion and the transported sediment will reduce surface water storage capacity. In suburban areas, it leads to economic loss due to property damage.

1.1 Regional Indicators and Impacts Related to Climate Change

Since the start of the industrial revolution, the concentration of CO_2 in the atmosphere has increased by roughly 35 percent (Diamond et al. 2013) As of May 2012, CO_2 measurement from the Hawaii's Mauna Loa Observatory was 396.78 parts per million (ppm). Over the last 800,000 years, atmospheric carbon dioxide (CO_2) concentrations have varied within a range of about 170 to 300 ppm.

In the Western North Pacific Ocean (WNPO), where Guam is located, observed maximum and minimum surface air temperatures increased over the past 60 years (Keener et al. 2012). Figure 1.2 below depicts maximum monthly temperature anomaly time series from 1952 to 2012 (using 1960– 1990 as the mean reference period) for single monitoring stations with the most data in Yap, Guam, and Palau. The northern hemisphere temperature time series (purple line, Hadley CRu NH) is superimposed for comparison.

Trends in maximum temperatures in the western part of the Western North Pacific sub-region appear to be increasing at the same general rate as average northern hemisphere temperatures, although Yap shows a high level of variability (Keener et al. 2012).

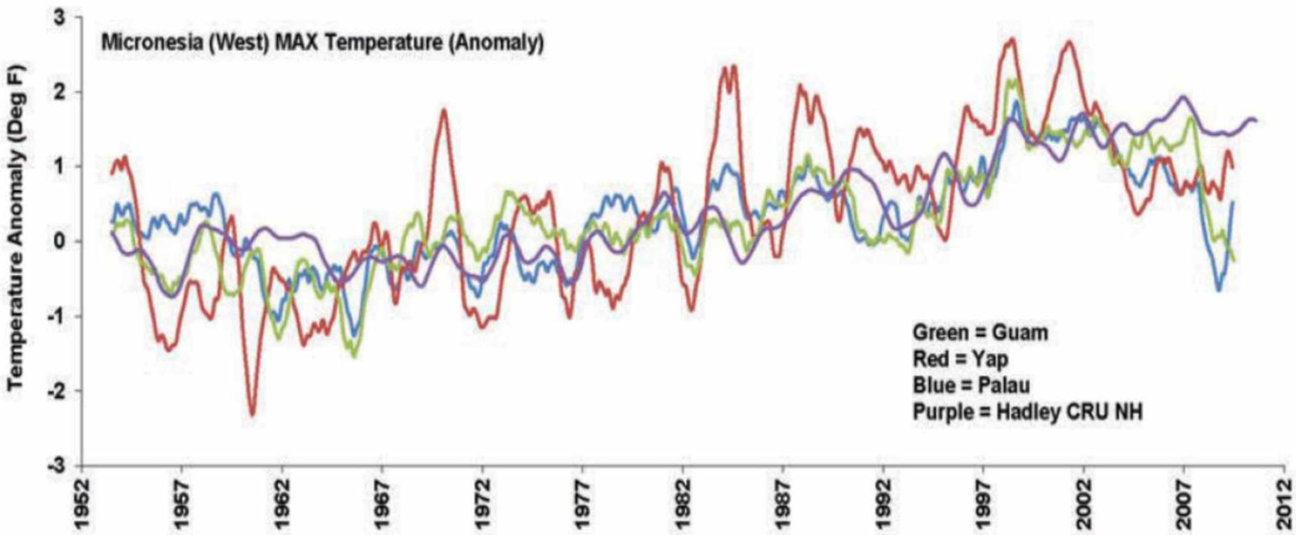


Figure 1.2 Maximum monthly temperature anomaly time series in West Micronesia from 1952 to 2012 (using 1960-1990 as the mean reference period) for single monitoring stations with the most data in Yap, Guam and Palau. The mean northern hemisphere temperature time series (purple line, Hadley CRu NH) is superimposed for comparison.

Global mean sea level has been rising at an average rate of approximately 0.13 inches +/- 0.02 inches (3.4 mm +/- 0.4 mm) per year since the early 1990s. This rate, based on satellite altimeter measurements, is twice the estimated rate for the 20th century based on tide-gauge measurements. The highest sea level rise (SLR) increases occur in the WNP. Regional changes exceeding the global average are attributed to changes in wind, as well as natural climate variability.

Globally, much of the SLR to date is a result of thermal expansion associated with ocean warming. The global rate is expected to increase as melting land ice adds water to the ocean.

Since the 1970s, sea-surface temperature (SST) has increased at a rate of 0.13° to 0.41°F (0.07° to 0.23°C) per decade, depending on the location. Projected increases in SST for the Pacific Islands region range from 1.1° to 1.3°F by 2030, 1.6° to 2.5°F by 2055, and 2.3° to 4.9°F by 2090 under varying emission scenarios.

When human-induced carbon dioxide is absorbed by seawater, chemical reactions occur that reduce saturation states of the minerals calcite and aragonite (a process referred to as ocean acidification). Surface pH has dropped by 0.1 pH units and is projected to decline an additional 0.2 to 0.3 pH units by 2011. (Keener et al. 2012).Aragonite is critical to reef-building coral, and annual maximum saturation state is projected to drop below 3.5 by 2035 to 2060 around the Pacific with continuing decline thereafter.

In the WNPO, the strength of the trade winds has increased since the early 1990s; correspondingly, sea level has risen. Observations from wave buoys suggest that wave heights have increased in this region over the past century. Majuro Atoll in the Marshall Islands and Kiribati, have already experienced coastal flooding and decreased extent of the vegetated wetlands due to the rise in sea level. (Ambalam 2014)

Existing climate models indicate that a 10% reduction in average rainfall by 2050 is likely to correspond to a 20% reduction in the size of freshwater lens on Tarawa Atoll, Kiribati (images shown in Figure 1.3) located in the central Pacific Ocean.

Furthermore, decline in the size of the islands, resulting from land loss accompanying sea-level rise, is expected to reduce the depth of the freshwater lens on atolls by as much as 29%.

Less rainfall coupled with accelerated sea-level rise would compound this threat. Lower rainfall typically leads to a reduction in the amount of water that can be physically harvested, to a reduction in river flow, and to a slower rate of recharge of the freshwater lens, which can result in prolonged droughts and water insecurity.

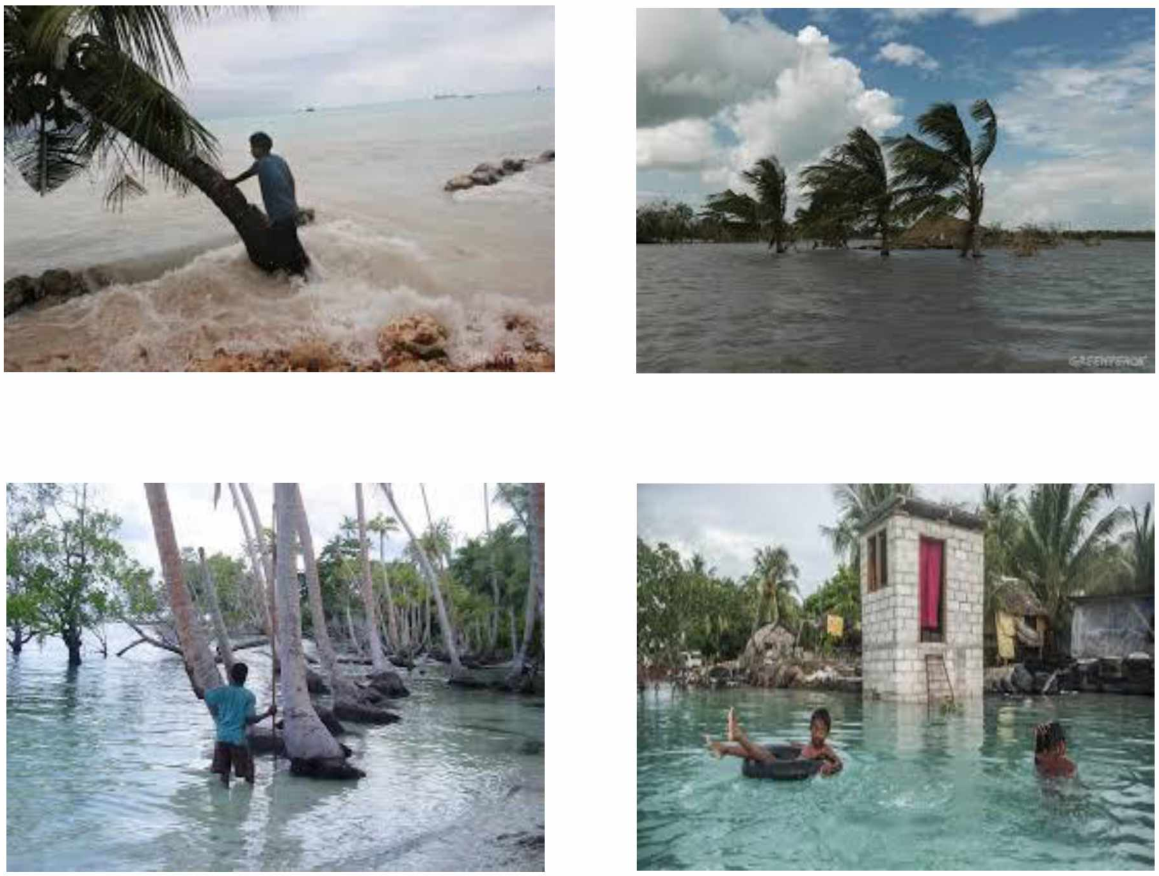


Figure 1.3 Rise of Sea Level in Kiribati Islands is depicted by the above Pictures Courtesy of greanpeace.org, pinterest.com, stuff.co.nz

A more detailed study shows that in Bonriki Island in Tarawa, a 50 centimeter rise in sea level, coupled with 25% reduction in rainfall could reduce the freshwater lens by 65%. Increase in sea level may also shift the fresh water table close to or above the land surface resulting in increased evapotranspiration thus diminishing the resource (Mimura et al. 2007).

Existing concerns play a great role in the water resources of the islands located in the Western Pacific region. These issues will be exacerbated given the increase in population on the islands. The loss of land mass is so great that Kiribati is considering moving its entire population to new land purchased from neighboring Fiji. Tuvalu, and even Fiji itself, may eventually face the same problem (Rolfe 2014).

Due to its importance, in 2010, the United Nations declared water/sanitation a human right. The Pacific is the only region in the world to be measured as not progressing positively in water and sanitation goals. For example, the Pacific island country of Tuvalu faces ongoing challenges in its water security. A series of atolls with permeable nature of their land means that surface water does not exist, and residents rely heavily upon rainwater for supplies. The water lens below the main island of Funafuti provides an emergency source of water for washing during droughts but is too saline for human consumption. When rainwater is scarce, the island also draws on reserves in the form of desalinated water, but this is expensive. Access to sufficient clean rainwater is therefore key to survival and human development. However, in the face of climate change, variability of rainfall increases concerns about the future supply of water on the islands.

Impacts of climate change on the already severely strained freshwater resources of approximately 1000 inhabited islands in the Pacific Ocean are a well-established fact (Gillespie and Burns 2000)

Major water security changes are related to temperature, rainfall, and sea level rise that are responsible for accelerated coastal erosion, saline intrusion into freshwater lenses and increased flooding from the sea which impact human settlements immensely (Ambalam 2014).

1.2 Guam's Presently Available Freshwater

The ironic and tragic aspect of the environmental crisis of greenhouse emissions is the fact that those parts of the world least responsible for creating the climate change/global warming problem are the first to suffer its horrifying consequences. Pacific Island Nations are responsible for only 0.03 percent of the world's carbon dioxide emissions, and the average island resident produces only one-quarter of the emissions of the average person worldwide (Gillespie and Burns 2000)

The Western Pacific region without a doubt is the world's most vulnerable when it comes to risk of disaster particularly for the several of the low-lying coral islands. Dramatic impacts have already been felt regarding water resources, agriculture, forestry, tourism and other industry-related sectors. Although the initial review of the existing models for the Western Pacific region (where Guam is located) predicted a reduction in precipitation and an increase in rainfall for the central and eastern pacific regions, the trend now appears to be the reverse (Gillespie and Burns 2000). In addition, increase in the greenhouse gas emissions is causing rise in ocean surface water temperatures that results in a greater exchange of energy and further development of cyclones and typhoons of higher frequencies by as much as 50-60 percent and increased intensities by 10-20 percent.

The island of Guam, a U.S. Territory is 30 miles long and 9 miles wide, with an area of 212 square miles, located 6,000 miles southwest of San Francisco, California and 3,700 miles west-southwest of Honolulu, Hawaii (Figure 1.4). The present population is approximately 174,000 including an estimated 14,000 active duty military personnel.

Guam’s mean annual rainfall from 1973 through 2010 from the recording at Andersen Airforce Base is computed at about 86 inches with the minimum annual rainfall that occurred in 1993 and the maximum annual rainfall that occurred in 1976 (Simard et al. 2015).

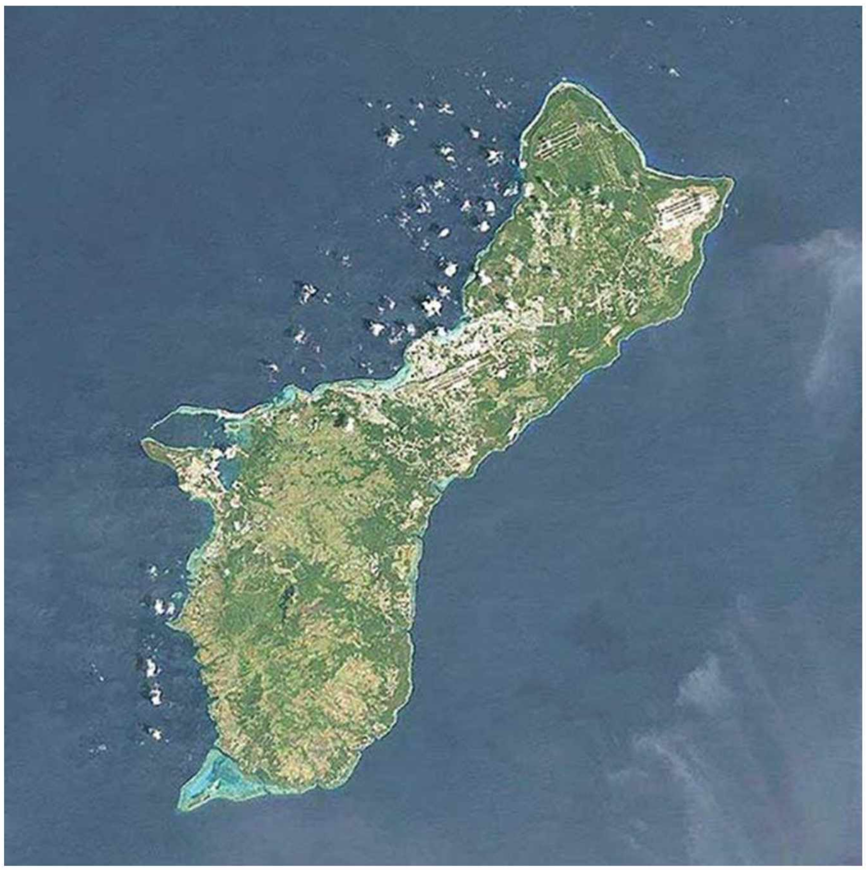


Figure 1.4 Areal View of Guam Island

Seismic events are common on Guam. The most significant event of recent years occurred in 1993 with a magnitude of 8.1 on the Richter scale. Guam’s proximity to the Challenger Deep, Mariana Trench is depicted in Figure 1.5

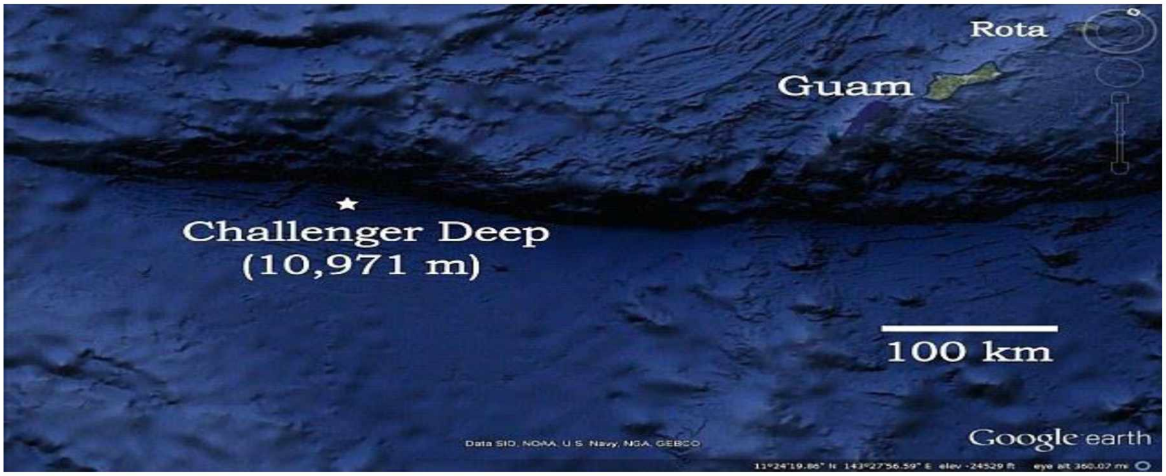
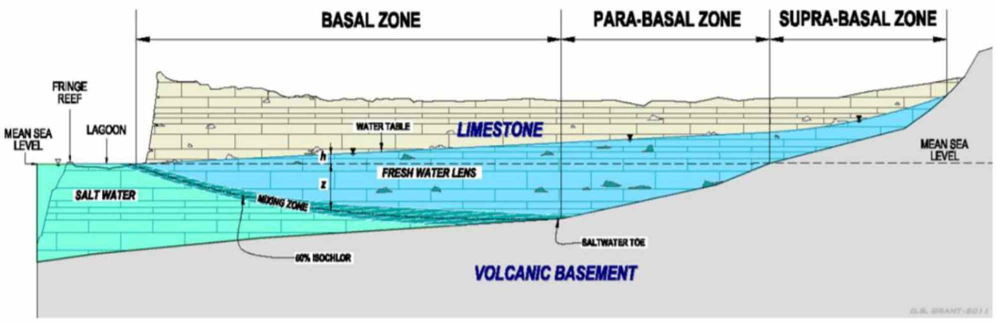


Figure 1.5 Guam Proximity to Mariana Trench

Guam geology is such that the rivers and streams only exist within the southern part of the island with soils of low permeability developed from highly weathered volcanic rocks. Highly permeable limestone found in the Northern half of the island with full permeability characteristics is the cause for recharging of the groundwater with no surface water streams in existence (Figure 1.6). Water levels in the freshwater lens vary several feet daily and seasonally in response to ocean tides, recharge, and ground-water withdrawal. Guam's surface water on the other hand, suffers from poor ground cover often exhibited by severe soil surface erosion at the watersheds. Following a prolonged drought period and initiated by a commonly occurring heavy precipitation event, there exists an extensive transport of sediments into the island's two surface water treatment facilities.



Volcanic basement beneath limestone aquifer defines three groundwater zones: 1) the basal zone, where the fresh water lens is underlain by sea water, 2) the para-basal zone, where the fresh water is underlain by the volcanic rock, and 3) the supra-basal zone, where the fresh water moving down-slope toward the para-basal zone is lies above sea level.

Figure 1.6 Typical Groundwater Zones on Guam Courtesy of WERI University of Guam

See Figure 1.7 for a map of Guam's river tributaries and watersheds. Ground water supplies about 80 percent of the drinking water for the islands residents and over one million visitors per year. In northern Guam, water is obtained from wells tapping a fresh ground-water lens in a highly permeable limestone aquifer. Nearly 180 wells withdraw about 35 Mgal/d of water with chloride concentrations ranging from 6 to 585 mg/L. In southern Guam, where low-permeability volcanic rocks are exposed over most of the area, about 9.9 Mgal/d of freshwater is obtained from surface reservoirs. Ground-water withdrawal has led to localized areas of increased chloride concentration via upconing, and other means of saltwater intrusion such as shifting of the saltwater-freshwater zone upward due to rise of sea level.

Figure 1.7 Typical Southern Guam Rivers and Corresponding Watersheds Courtesy of WERI, University of Guam

Factors that may contribute to the high concentrations of chlorides in drinking water include 1) excessive rates of ground-water withdrawal from a single well, 2) a cluster of wells too closely spaced, 3) wells that are drilled too deeply into the freshwater lens, and 4) higher permeability geologic units that allow increased mixing of freshwater with the underlying saltwater.

1.3 Population Issue

An estimated total 5,000 Marines and 1,300 dependents are expected to relocate from Okinawa, Japan to Guam by year 2020. This relocation is considered a component of the Military Force Realignment Program in the Asia-Pacific Region. The direct increase in the number of active duty personnel and their dependents has been estimated to bring in an additional 3,000 to 4,000 construction workers and support staff to the island. An overall increase of 15,000 to Guam's population above and beyond the natural growth has been predicted by some estimates by 2020. In addition, the natural growth in population combined with the increase in tourism will increase freshwater demand to the extent that the island's water security may be impacted in the foreseeable future.

1.4 Objectives and Methods

This research uses existing data for Guam to serve as potential water security indicators to determine if any impacts on Guam's water quality and quantity is conceivable and can be identified. If loss of resource is determined, the research will make sustainable water resources adaptive management recommendations that could address new strategies required to overcome potential deficiencies. The data collection and analysis are provided from a purely quantitative approach.

The following sources of data on Guam have been identified and examined utilizing historical data. The major climate change indicators compiled and analyzed for this research include:

1. Intensity of ENSO weather phenomenon (Pearcd 2016);

2. Precipitation and potential trends;
3. Storm occurrence, intensity and frequency;
4. Air temperature;
5. Ocean surface water temperature;
6. Ocean water quality; and
7. Sea level.

A sustainable freshwater resources management plan both from quality and quantity standpoints can be developed for a water secured Guam based on the following related factors among others:

1. Existing freshwater availability and accessibility;
2. Existing water quality;
3. Groundwater chloride levels specifically during dry years;
4. Surface water turbidity, and concentration of suspended solids specifically during a heavy precipitation event following a dry period;
5. Water balance computations and analysis using data from the historical dry years for the projected future demands on the water infrastructure (population increase impacts due to natural growth, tourism, and military relocation).

Chapter 2 Extent of Climate Change Impacts on Guam

In order to obtain information, reports and opinions required to achieve the goals of this research, web-based data were compiled from several sources including but not limited to the following organizations:

- Guam Environmental Protection Agency (GEPA);
- Guam Waterworks Authority (GWA);
- United States Geological Survey (USGS);
- National Oceanic and Atmospheric Agency (NOAA);

Water and Environmental Research Institute, University of Guam (WERI)

2.1 Data Collection and Methods

The data attempted to address the following two research questions:

1. Is there evidence of climate change on the water security of Guam?
2. Could the global climate change impacts and local anthropogenic factors impact Guam's water security?

The research approach is quantitative, and the sources of information consists of historical data and potential climate change prediction models. Potential Climate Change Indicators used for Guam are listed below:

- Frequency and Intensity of ENSO Weather Phenomenon;
- Precipitation Trends;
- Storm Occurrence, Intensity and Frequency;
- Air Temperature;

- Water Temperature;
- Ocean Water pH;
- Sea Level.

2.2 Frequency and Intensity of El Nino Southern Oscillation (ENSO) Weather Phenomenon

El Niño is a unique weather pattern that is caused by the warming of the Pacific Ocean near the equator, off the coast of South America. This occurs when the normal trade winds weaken (or even reverse), which lets the warm water that is usually found in the western Pacific flow instead towards the east. Climatologists agree that there have been three "super-El Niños" in the space of just over three decades in 1982-83, 1997-98, and now 2015-16. This unusual recurrence supports the forecast made that super El Niños are in the process of upgrading from once every 20 years to once every ten years (Cai et al. 2014)

Climate models predict doubling of the El Niños occurrences in the future in response to greenhouse warming. The increased frequency arises from a projected surface warming over the eastern equatorial Pacific that occurs faster than in the surrounding ocean waters, facilitating more occurrences of atmospheric convection in the eastern equatorial region. (Cai et al. 2014)

It is important to point out that El Niño events are occurring more frequently on Guam than once every 10 years. Historical precipitation data at the Guam International Airport indicates that in the course of approximately 70 years (1945 to present) about 12 ENSO events have developed on Guam that can be translated to an average frequency of every 6 years. This finding is confirmed (Simard et al. 2015), WERI UOG finding while utilizing data from a rain gage located in Guam's Anderson Airforce Base.

As seen by the historical precipitation data depicted below and confirmed by the years indicated in red showing the year after each El Niño events, which tend to be characterized by drought conditions. Updated figure from (Simard et al. 2015).

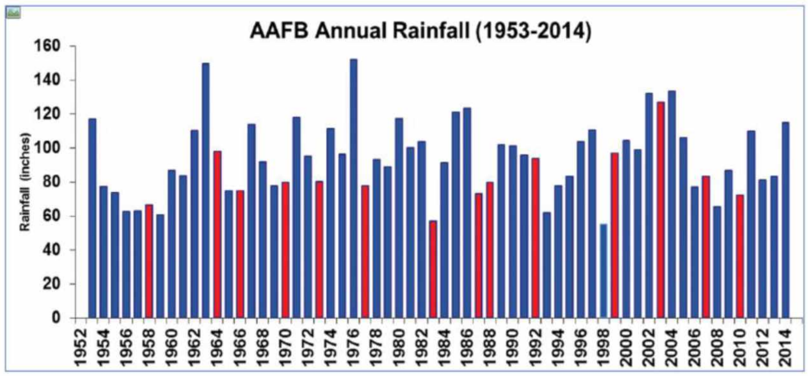


Figure 2.1 Annual Total Rainfall Depth at the Andersen Air Force Base.

The following precipitation data from 1945 through 2016 was tabulated from raw data that were provided by NOAA in a single station located at the Guam International Airport.

Table 2.1 Monthly and Annual Total Precipitation at Guam International Airport, Courtesy of NOAA

Monthly Total Precipitation for GUAM INTL AP, GU

Click column heading to sort ascending, click again to sort descending.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1945	M	M	M	M	M	M	M	M	14.66	11.16	2.57	2.55	30.94
1946	4.02	0.91	M	M	M	M	M	M	M	M	M	M	4.93
1947	M	M	M	M	10.16	3.30	8.47	9.81	10.54	14.64	10.44	5.29	72.65
1948	8.25	1.51	0.71	5.36	4.38	8.16	4.92	12.61	9.15	13.32	12.56	5.43	86.36
1949	3.47	1.05	2.48	2.55	1.67	2.91	8.73	12.66	14.18	12.65	5.89	2.50	70.74
1950	1.67	1.79	1.97	1.11	8.75	7.38	12.17	8.79	21.56	14.07	7.38	5.16	91.80
1951	5.48	5.92	4.21	6.42	0.78	1.56	5.52	16.80	3.91	16.82	9.10	7.27	83.79
1952	2.53	0.67	0.69	1.42	5.02	2.99	9.36	11.58	14.74	13.37	12.56	8.45	83.38
1953	1.57	9.21	1.51	0.67	2.23	1.76	7.30	23.29	9.83	26.47	11.63	5.61	101.08
1954	5.80	1.75	1.10	1.81	2.19	4.34	4.46	11.33	18.59	12.90	11.55	3.34	79.16
1955	6.38	2.46	1.73	2.95	4.09	4.06	15.28	7.42	17.63	9.27	5.74	4.28	81.29
1956	2.27	2.82	2.14	2.39	5.59	3.04	9.03	7.37	16.02	9.20	13.82	8.25	81.94
1957	3.55	2.10	2.22	2.41	1.70	3.73	4.74	9.33	11.70	13.59	14.50	2.14	71.71
1958	5.93	1.94	0.58	2.50	3.22	7.78	10.55	11.73	14.08	10.91	8.03	3.80	81.05
1959	2.42	1.31	1.47	2.61	0.83	1.20	5.02	12.57	15.67	8.36	6.40	3.76	61.62
1960	2.67	0.31	1.59	1.11	5.12	4.75	6.30	11.02	9.88	10.32	8.67	7.93	69.67
1961	5.98	2.30	3.92	4.46	4.31	6.33	6.00	16.62	12.55	16.21	7.18	5.02	90.88
1962	1.63	3.93	1.51	7.35	6.03	9.72	17.69	17.94	15.19	11.29	4.16	8.07	104.51
1963	11.14	7.26	2.06	15.28	15.02	5.81	8.74	7.20	12.85	16.82	5.77	8.43	116.38
1964	1.95	2.65	1.31	8.91	14.33	4.86	10.30	8.65	12.79	9.05	4.83	5.84	85.47
1965	11.51	1.38	0.82	0.62	1.89	4.10	15.31	3.91	17.57	7.48	5.53	2.67	72.79
1966	1.92	1.12	1.20	0.51	1.36	5.18	5.18	13.65	20.71	6.53	8.47	3.68	69.51
1967	4.85	2.77	7.49	6.74	3.99	11.66	12.04	19.05	20.39	13.64	9.17	2.07	113.86
1968	4.96	7.43	3.44	2.39	2.36	6.70	11.00	14.42	14.45	17.71	11.26	1.88	98.00
1969	2.20	1.85	2.70	3.03	4.17	1.30	11.98	10.22	8.66	18.19	9.25	8.42	81.97
1970	8.32	2.47	1.95	1.17	2.12	5.40	7.22	8.07	11.53	8.11	6.99	3.96	67.31
1971	4.77	5.05	7.28	3.89	16.01	5.29	14.79	15.28	8.56	7.27	6.81	2.15	97.15
1972	4.05	3.29	4.32	1.79	2.57	4.52	13.51	15.14	11.81	5.32	2.78	3.13	72.23
1973	1.15	1.71	0.89	1.09	1.65	3.57	6.04	9.50	8.08	15.55	2.73	7.18	59.14
1974	2.76	1.81	9.27	10.41	13.22	8.03	12.83	21.42	8.25	11.08	6.41	5.46	110.95
1975	7.14	0.60	1.72	2.31	1.27	2.07	9.66	14.49	7.64	12.04	10.72	2.68	72.34

Table 2.1 Cont.

1976	18.09	9.25	7.73	3.99	24.07	6.38	14.06	18.44	10.33	4.27	10.35	4.74	131.70
1977	1.82	1.95	3.81	1.25	3.91	4.35	5.82	4.11	13.70	15.47	9.13	2.19	67.51
1978	0.99	2.15	0.40	2.16	3.86	11.19	10.94	16.28	9.85	10.14	16.15	3.88	87.99
1979	2.71	1.06	3.45	1.50	1.60	3.21	7.33	10.37	11.55	25.25	9.29	5.07	82.39
1980	1.21	13.87	2.74	2.77	11.34	9.90	9.69	10.76	23.90	11.08	5.85	6.66	109.77
1981	4.25	0.69	1.28	5.30	4.11	7.78	14.44	24.33	11.23	12.05	11.61	7.84	104.91
1982	1.89	6.01	1.43	0.68	7.94	8.89	9.81	10.52	24.34	15.08	5.99	5.25	97.83
1983	0.95	0.61	2.73	0.53	2.01	0.83	7.21	13.56	10.05	7.95	10.14	4.48	61.05
1984	3.50	2.93	3.30	2.15	3.15	8.43	6.50	18.22	12.69	8.87	11.90	4.99	86.63
1985	5.71	1.77	3.57	4.48	12.12	13.33	9.81	14.43	16.87	7.97	3.71	6.51	100.28
1986	1.13	5.75	3.31	3.59	7.81	5.98	16.77	24.36	8.70	17.34	3.73	8.70	107.17
1987	1.91	4.89	1.46	1.56	0.40	3.04	14.58	8.47	10.22	12.41	9.01	5.92	73.87
1988	5.74	0.90	0.94	2.55	2.69	10.67	9.25	9.37	8.85	17.71	5.93	2.32	76.92
1989	5.02	11.71	0.80	10.27	4.68	10.31	10.29	11.42	15.96	17.45	8.43	3.16	109.50
1990	12.25	1.82	1.38	2.41	4.38	6.97	7.94	17.19	18.11	7.25	11.58	15.94	107.22
1991	2.89	3.55	1.41	4.62	4.93	5.55	7.79	17.84	10.28	10.77	13.05	3.66	86.34
1992	6.23	0.53	2.01	1.33	2.01	3.70	8.84	24.26	8.43	12.74	9.65	1.57	81.30
1993	1.37	2.83	1.11	0.91	1.38	1.46	7.05	15.04	10.96	14.40	7.82	5.24	69.57
1994	3.85	1.60	3.55	3.96	8.41	3.58	18.46	7.04	18.90	11.12	3.02	4.75	88.24
1995	1.81	0.83	1.45	M	M	M	M	M	M	M	M	M	4.09
1996	M	M	M	M	M	M	M	M	M	M	M	M	M
1997	M	M	M	M	M	M	M	M	M	M	M	M	M
1998	1.99	1.22	0.97	1.51	1.05	4.52	5.38	4.44	16.44	9.64	6.78	3.94	57.88
1999	4.70	12.59	1.91	3.68	3.53	10.41	12.81	8.39	11.94	7.98	5.42	3.51	86.87
2000	2.79	4.92	4.03	1.65	7.44	4.74	6.16	18.62	12.63	11.40	5.16	8.85	88.39
2001	2.90	3.21	2.13	1.15	2.27	13.12	15.53	24.83	7.40	11.48	12.76	6.17	102.95
2002	8.46	5.55	3.05	1.34	6.32	7.13	29.80	20.53	17.19	7.02	6.94	5.68	119.01
2003	2.45	3.13	5.40	5.87	2.91	6.17	10.16	9.51	21.73	12.65	20.33	11.94	112.25
2004	4.17	6.94	3.42	3.38	5.51	22.03	10.11	37.32	10.85	9.87	6.46	3.27	123.33
2005	1.55	5.17	2.47	2.50	2.40	8.58	9.72	17.98	17.29	12.10	5.98	3.36	89.10
2006	6.80	4.45	0.98	0.96	2.15	8.84	20.18	12.07	8.94	15.39	5.11	3.97	89.84
2007	4.24	1.36	2.37	1.92	8.77	1.93	7.40	16.01	13.58	14.44	13.29	2.68	87.99
2008	3.07	8.02	1.99	3.08	2.79	5.39	10.42	7.84	15.47	7.21	4.79	3.30	73.37
2009	4.53	1.90	3.06	3.03	3.57	4.58	10.72	26.14	15.54	11.13	5.08	7.85	97.13
2010	4.69	1.06	4.40	2.16	0.74	5.33	12.09	12.18	12.15	13.54	4.38	4.09	76.81
2011	9.11	6.21	4.12	5.56	5.77	5.96	20.54	15.00	16.37	15.45	6.14	5.24	115.47
2012	6.50	2.85	4.45	3.05	7.63	6.63	6.74	26.42	15.98	10.56	5.45	2.81	99.07
2013	5.12	2.95	3.95	1.14	3.51	6.32	5.39	10.84	32.24	22.66	4.13	3.33	101.58
2014	16.89	5.14	2.91	2.74	3.36	6.08	29.39	9.08	14.72	18.77	5.51	3.87	118.46
2015	8.56	0.18	4.09	6.65	9.91	5.32	21.80	21.54	13.71	14.26	5.96	3.77	115.75
2016	2.62	3.63	1.63	1.31	1.80	7.73	6.77	20.85	15.65	13.14	10.13	8.68	93.94
Mean	4.63	3.45	2.65	3.21	5.05	6.09	10.77	14.29	13.79	12.52	8.07	5.08	86.40
Max	18.09 1976	13.87 1980	9.27 1974	15.28 1963	24.07 1976	22.03 2004	29.80 2002	37.32 2004	32.24 2013	26.47 1953	20.33 2003	15.94 1990	131.70 1976
Min	0.95 1983	0.18 2015	0.40 1978	0.51 1966	0.40 1987	0.83 1983	4.46 1954	3.91 1965	3.91 1951	4.27 1976	2.57 1945	1.57 1992	4.09 1995

The tabulated rainfall data were plotted in Figure 2.2 and includes a linear regression line represented by the equation Y = 0.25X + 80.55. The slope of the linear regression was determined to be 0.25, meaning an average increase of 0.25 inches of rainfall each year. Although there exists several years within the 72-year period, when the total annual rainfall was quite low (apparently caused by the El Nino Southern Oscillation "ENSO" effect), the slope of the regression line is representing a general precipitation upswing trend for the island. A Pearson Correlation Factor of r = 0.31 was calculated between the year and the annual precipitation. Although this value is considered a positive however a weak relationship, the $p<0.01$ indicates that the statistically significant results here are not caused by chance.

Whether the trend of increase in precipitation will continue for years to come is unknown at this point. In fact, some climate change models predicted a decrease in rainfall for the Western Pacific and increase in rainfall for the Central and Eastern Pacific Region. It appears that for the time being, the above prediction has not yet materialized, and the trend thus far has been the reverse. For example, the Hawaii Islands' (East/Central Pacific) latest rainfall data show a downward trend (Keener 2012)

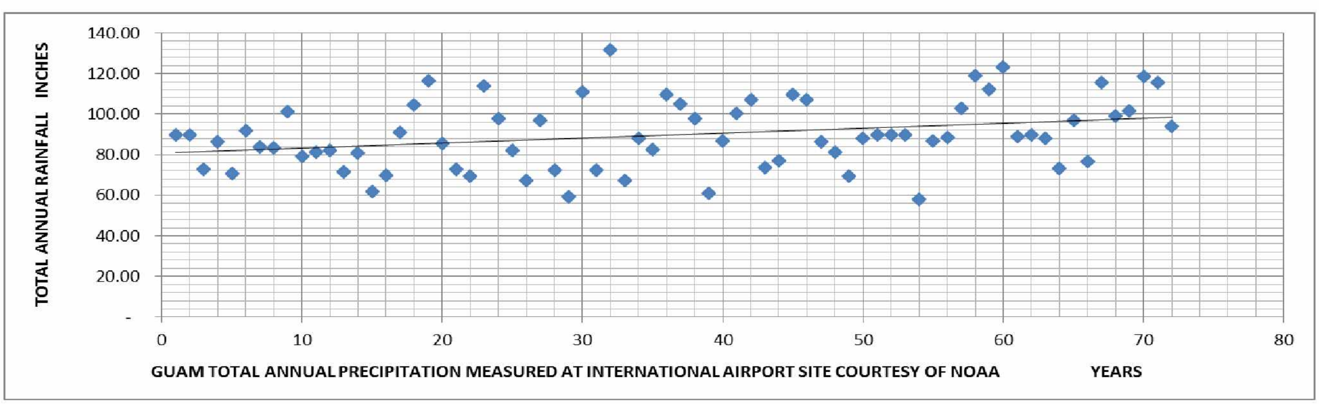


Figure 2.2 Annual Total Precipitation at the Guam International Airport, Courtesy of NOAA

2.3 Storm Occurrence, Intensity and Frequency

Typhoons are strong tropical storms that occur in the Western Pacific Ocean with wind speeds exceeding 74 miles per hour. Typhoon occurrences on Guam averaged as once every 8 years during 1800s. During 1900s the occurrences averaged as once every 6 years (U.S. Naval Oceanography Command Center Joint Typhoon Warning Center COMNAVMARIANAS Tech Note 91-2). Direct impact on Guam (storm's eye passing directly over the island) by typhoons that were primarily developed south-east of Guam and their related intensities from 1991 until present is summarized below:

- Typhoon Yuri — November 1991 — Sustained winds of 165 mph
- Typhoon Omar — August 1992 — Sustained winds of 150 mph
- Typhoon Paka — December 1997 — Gusts up to 236 mph
- Typhoon Chataan — July 2002 — Sustained winds 110 mph
- Typhoon Pongsona — December 2002 — Gusts up to 240 mph

Typhoon events with direct impacts on Guam have been surprisingly nonexistent from 2003 till present. The typhoon alley through Guam has been quiet in the past 14 years indicative of a departure from the previous trend. During the recent years however, some tropical storms over Guam have primarily travelled north-west and have intensified to become great typhoons severely impacting Philippines, Japan, Taiwan, and China (East Asia in general).

2.4 Surface Air Temperature

Historical highest annual air temperature data (Fahrenheit) was compiled from the NOAA website from 1945 through 2014 at the Guam International Airport. These data were tabulated and summarized as provided in Table 2.2:

Table 2.2 Highest Annual Surface Air Temprature at Guam International Airport, Courtesy of NOAA

YEAR	1,945	1,946	1,947	1,948	1,949	1,950	1,951	1,952	1,953	1,954	1,955	1,956
TEMP	89	93	92	90	90	90	92	91	92	90	90	90

YEAR	1,957	1,958	1,959	1,960	1,961	1,962	1,963	1,964	1,965	1,966	1,967	1,968
TEMP	91	89	90	88	91	92	94	93	92	93	92	90

YEAR	1,969	1,970	1,971	1,972	1,973	1,974	1,975	1,976	1,977	1,978	1,979	1,980
TEMP	95	93	96	90	90	94	89	91	91	91	92	92

YEAR	1,981	1,982	1,983	1,984	1,985	1,986	1,987	1,988	1,989	1,990	1,991	1,992
TEMP	93	93	93	94	93	93	94	93	94	96	93	92

YEAR	1,993	1,994	1,995	1,996	1,997	1,998	1,999	2,000	2,001	2,002	2,003	2,004
TEMP	93	94	88	92	92	90	91	91	92	91	91	91

YEAR	2,005	2,006	2,007	2,008	2,009	2,010	2,011	2,012	2,013	2,014	2,015	2,016
TEMP	94	92	92	91	91	92	91	92	93	93	91	94

The maximum annual temperature data were plotted in Figure 2.3 to include a linear regression line of Y = 0.02X + 91.09, resulting in a nonsignificant Pearson Correlation Factor of r = 0.24. The positive slope of 0.02 indicates a maximum temperature increase of 1.44 F over the Past 72 years, a general temperature upswing trend for the island. The highest temperature was measured at 96 degree Fahrenheit in 1971 and 1990. It appears that the data points are depicted such that a non-linear regression curve could also fit through. The maximum annual temperatures are potentially showing a nonsignificant trend for the 70+ year duration of data since 1945 to 2016.

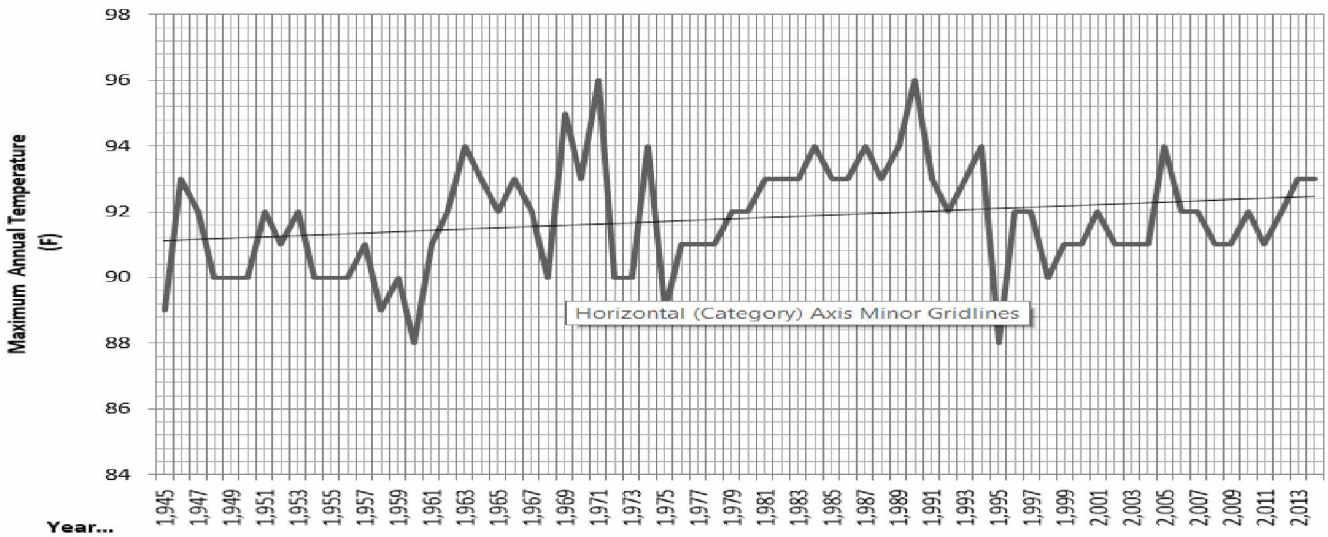


Figure 2.3 Maximum Annual Air Temperature at Guam International Airport, Courtesy of NOAA

To better investigate any potential trends, a summary of Guam's average annual surface air temperatures from historical data (also measured at the same NOAA weather Station located at the Guam International Airport) are provided in Table 2.3 and Figure 2.4.

Table 2.3 Average Annual Air Temperature at Guam International Airport, Courtesy of NOAA

Year	Average Annual Air Temp.
1945	91
1946	91
1947	91
1948	88
1949	88
1950	88
1951	89
1952	89
1953	89
1954	88
1955	87
1956	88
1957	88
1958	87
1959	87
1960	87
1961	87
1962	88
1963	89
1964	91
1965	89
1966	91
1967	89
1968	89
1969	91
1970	91
1971	91
1972	89
1973	89
1974	89
1975	87
1976	89
1977	88
1978	88
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1980	90
1981	91
1982	91
1983	91
1984	92
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1990	92
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1992	90
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1995	91
1996	91
1997	91
1998	89
1999	89
2000	89
2001	90
2002	89
2003	90
2004	89
2005	90
2006	90
2007	90
2008	90
2009	90
2010	90
2011	90
2012	90
2013	91
2014	91
2015	90
2016	91

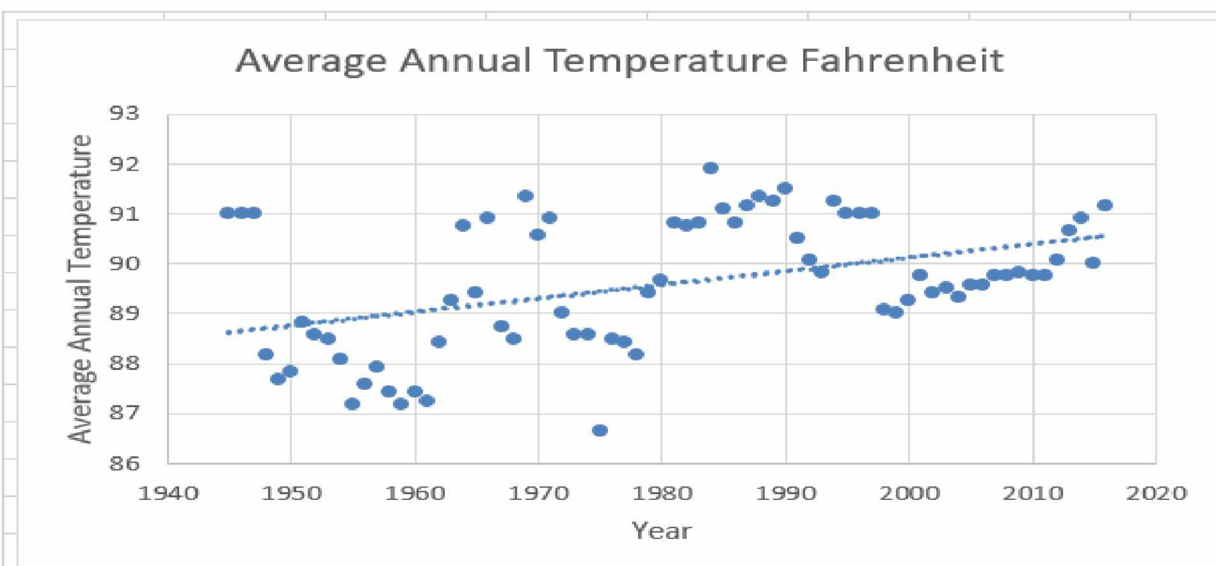

Figure 2.4 Average Annual Air Temperature at Guam International Airport, Courtesy of NOAA

A moderate Correlation Factor of r=0.47 indicates that the increase in the average surface air temperature is relevant throughout the 72 years of data. In addition, this correlation is statistically significant at the 98% confidence level, (p=0.02).

2.5 Sea Surface Water Temperature

Analysis of the historical ocean water temperature data for Guam reveals warming of the sea surface water of more than one degree Celsius over the last century, in addition to the year-to-year changes associated with the El Niño-Southern Oscillation (ENSO). Warming waters are likely to damage much of the coral around Guam. Rising water temperatures harm the algae that live inside corals and provide food for them. The loss of algae weakens corals and can eventually kill them. This process is commonly known as "coral bleaching" because the loss of the algae also causes the corals to turn white. Coral bleaching is becoming more common around Guam, including record-breaking bleaching that has occurred throughout the western Pacific since 2013. Elevated water temperatures also cause outbreaks of diseases that can harm or kill corals (U.S. EPA, 2016).

The following data represent the average annual ocean surface water temperatures of the coast of Ipan, Guam that were collected, compiled from the recorded hourly data by the NOAA Buoy # 52200 from 2004 through 2016. The data were plotted and analyzed for any potential trends. It appears that the ocean surface water temperatures of Guam show an upward trend for the past 13 years of available continuous data from the single station/location. A moderate correlation factor of r=0.50 for the average annual surface water temperatures exists for the past thirteen years of available data, shown in Figure 2.5.

		Years	Average Temp. C
		2004	29.12
		2005	28.85
		2006	28.97
		2007	28.97
		2008	29.26
		2009	29.24
		2010	28.84
		2011	29.13
		2012	29.14
	31.32	2013	29.21
29.21	29.89	2014	29.21
		2015	29.27
		2016	29.13

*Figures in Red are Adjusted Average of 2012 & 2015 (average annual temps)

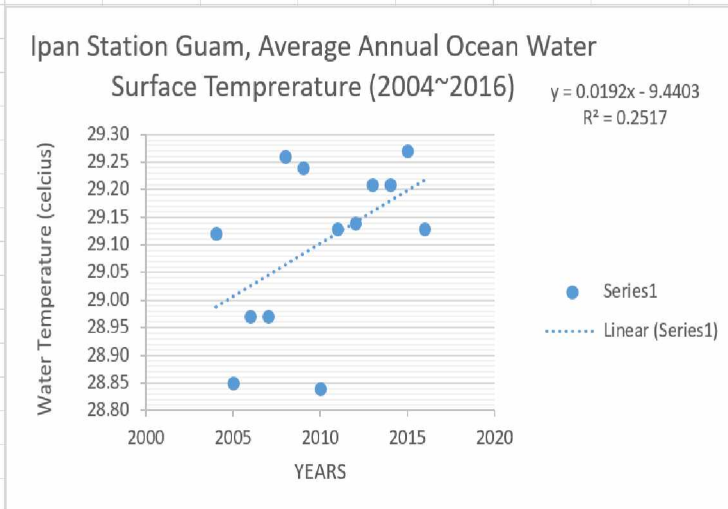

Figure 2.5 Average Annual Ocean Surface Water Temperature at Ipan, Guam Data Collected by NOAA Buoy #52200

2.6 Ocean Water pH

Greenhouse gases are widely accepted to be changing the world's oceans and ice cover. Carbon dioxide available in the air reacts with the ocean waters to form carbonic acid. Hence, the oceans are becoming more acidic. Since the beginning of the Industrial Revolution, the pH of surface ocean waters has fallen by 0.1 pH units. Since the pH scale, like the Richter scale, is logarithmic, this change represents approximately a 30 percent increase in acidity. Future predictions indicate that the oceans will continue to absorb carbon dioxide and become even more acidic. Estimates of future carbon dioxide levels, based on business as usual emission scenarios, indicate that by the end of this century the surface waters of the ocean could be nearly 150 percent more acidic, resulting in a pH that the oceans haven't experienced for more than 20 million years (U.S. EPA 2016). The Pacific Ocean has become more acidic as shown in the carbon dioxide time series for the North Pacific as shown (in color blue) in Figure 2.6.

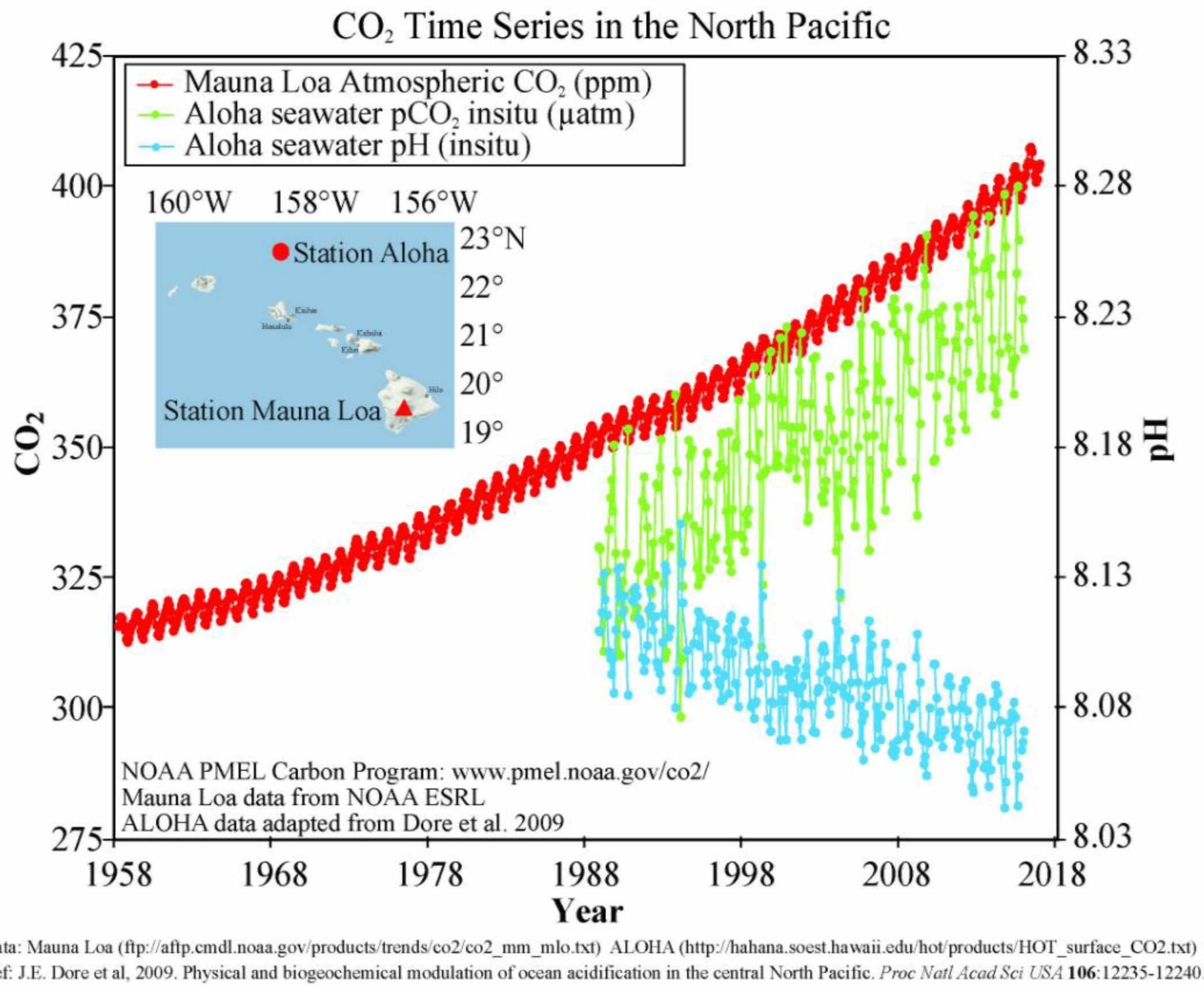

Figure 2.6 North Pacific Atmospheric CO_2 and Pacific Ocean Surface Water pH Time Series

2.7 Sea Level

Mean sea level data on Guam were compiled from a tide gage starting in 1948 to 2014 and shown in Figure 2.7.

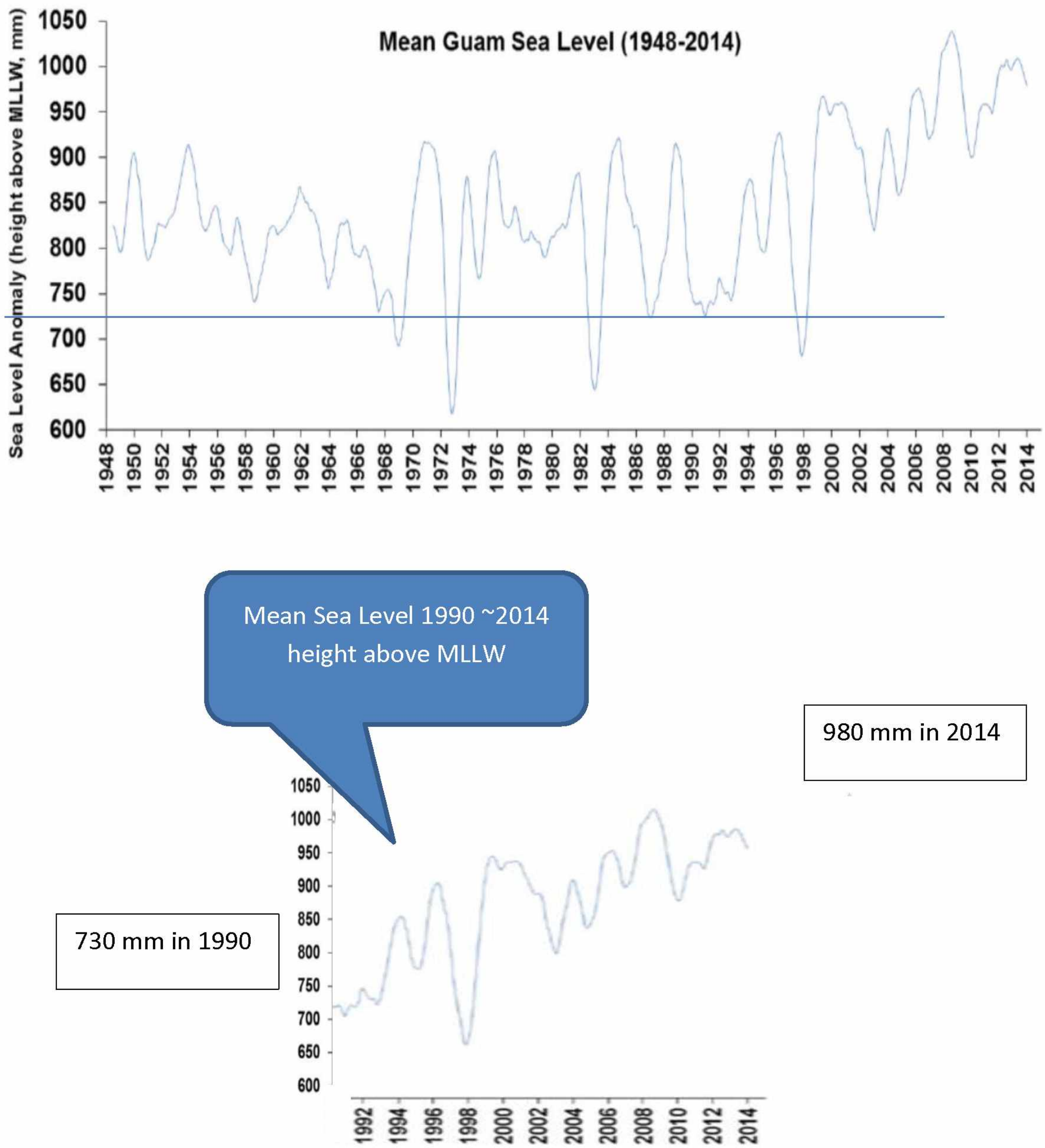

Figure 2.7 Sea level anomaly in mm (represented as height above mean lower low water, [MLLW]) as a 12-month moving average from Guam tide gage data. (Figure from Simard et al. 2015)

2.8 Summary

The analysis of several varying types of data and water information sources hint at evidence of impacts of climate change, however, not all potential indicators show significance. In summary, the water indicators versus evidence for Guam impact are provided below:

Indicators	**Significance**
Enso Weather Phenomenon	+
Precipitation Trends	-
Surface Air Temperature	+
Ocean Surface water temperature	+
Ocean water PH	+
Sea Level Rise	+

All indicators except for the precipitation support the hypotheses that climate change trends are impacting Guam's water security. This will eventually weaken Guam's resilience.

Chapter 3 Guam's Fresh Water Resources at its Present State and Potential Impacts

A possible impact of climate change on Guam has already been proposed in Chapter 2. The impacts on temperature and sea level appear to be real trends and show signs of continual challenges related to the specific water security issues. For example, the increase in air and ocean surface water temperatures support potential increases in evapotranspiration. Surface water temperature may be responsible for the trend of increase in precipitation for past several years. The significantly severe drought years may forewarn of an extreme rain/drought cycle. A prolonged drought following a strong El Nino event would support this hypothesis and would impact the water security of Guam.

As the sea level rises, it impacts the freshwater resource by shifting the saltwater/freshwater transition zone upward. Due to the inherent irregularity of the limestone karst as the storage medium of the freshwater in northern Guam, this shift does not impact the freshwater at a linear one to one displacement (reduction) ratio. For example, a 6-inch rise of the sea level does not simply reduce the freshwater lens thickness by 6-inches. As the freshwater pushes upward and closer to the ground surface by the underlying sea water, a resource loss due to accelerated evapotranspiration is unavoidable. In general, the sea level rise will reduce the quantity and the quality of the fresh groundwater source. The sea level rise also contributes to degradation of the surface water quality especially at the river deltas where it impacts agriculture by saltwater intrusion into the river delta soils.

Also, as the ocean pH levels around Guam increases, the adverse impacts on regional ecosystems will be impacted via loss of the marine life, such as a coral.

A non-significant trend has been observed. Lastly, the moderate climatic change on Guam, suggests a review of the access to freshwater on Guam in light of the anticipated increase in population and other anthropogenic related impacts such as tourism.

3.1 Existing Freshwater Availability and Accessibility

The Northern Guam Lens Aquifer (NGLA) produces about 80% of the island's drinking water. In 2017, forty-three (43) million gallons per day (mgd) are extracted from 136 wells in the Northern Guam Groundwater Lens Aquifer. In Southern Guam, 10.3 mgd is extracted from the Fena Lake and about 2 mgd is produced from the Ugum River (total 12.3 mgd). The total production from all sources is presently approximated at 55.3 mgd. (Compiled from Guam Waterworks Authority technical Annual Reports).

3.2 Water Quality

The Northern Guam Lens Aquifer water is calcium carbonate rich (hard) water and is primarily described by its chloride contents for freshness. In Southern Guam, surface water (SGSW) quality is primarily described by its turbidity and the concentration of the suspended solids. The SGSW has low chloride and carbonate levels.

3.3 Groundwater Salinity and Chloride Levels

The Northern Guam Lens Aquifer provides 80% of Guam's drinking water (Guam Waterworks Authority Annual report 2017). The anticipated addition of US Marine Corps activities will require additional production, while ongoing economic growth will increase demand. Historical chloride concentration levels for 153 production wells from 1973 through 2010 was obtained from Technical Report Number 143 titled "Salinity in the Northern Guam Lens Aquifer" by Water Energy Research Institute (WERI), University of Guam.

Chloride concentrations in groundwater production wells has shown a significant increase from 1973 to 2010 (period of study) at 107 (70%) of the 153 wells. Increasing groundwater chloride concentration in the supra-basal groundwater zone, which is not hydraulically connected to underlying saltwater (see Figure 1.6) suggests that other sources of chloride, such as dissolved salts in rainfall or sea spray, or human-induced sources, are affecting the aquifer via the groundwater recharge process. Controlled studies are needed to address the source.

Trends indicate that chloride increases occur during the transition from El Nino to La Nina episodes, and that chloride decreases occur during the transition from La Nina to El Nino episodes. Some production wells exhibit a cyclical chloride trend with a 4-year to 6-year periodicity that appears to coincide with the El Nino/Southern Oscillation (ENSO). The rim of fresh water (NGLA) concentrated along the boundary of the volcanic basement and the associated water-table near sea level is underlain by volcanic rock rather than the sea water. This para-basal water is fresher, thicker and much less vulnerable to salt-water contamination than the basal water downstream, which floats on the underlying sea water and becomes progressively thinner and saltier until it discharges at coastal springs.

Water flowing down the flank of the volcanic slopes above sea level, designated supra-basal water, is the freshest of the water in the aquifer and is completely invulnerable to contamination by sea water (see Figure 1.6). The major ions in seawater are chloride, sodium, sulfate, magnesium, calcium, and potassium. The chloride ion accounts for over 55% of the total weight of dissolved salts and is the easiest salt to measure accurately (Simard et al. 2015). Chloride concentration is thus the customary index of groundwater salinity and is generally reported in milligrams per liter (mg/1). The U.S. EPA National Secondary Drinking Water Regulations lists the secondary (non-enforceable) standard for chloride as 250 mg/1.

Chloride concentration can be measured directly by laboratory titration or by chloride-specific electronic probes in the laboratory or field. For seawater and dilutions of seawater with pure freshwater the standard relationship is provided by the Equation 3.1.

$$S\text{‰} = 1.80655 \times 10^{-3}\text{‰} \cdot {}^{l}\!/_{mg}\left[\mathrm{Cl}^{-}\right] \qquad \text{(Equation 3.1)}$$

Where, S is percent salinity and Cl^- is chloride concentration in mg/l (Lewis 1980).

Seawater is the primary source of salt in the Northern Guam Ground Water Lens Aquifer (NGLA). Sea level rise may increase acidic ocean water (globally acidified ocean water) in contact with the limestone, an integral part of the Guam's groundwater system, and if so, lead to increased salinity at the transition zone. This would occur due to the porosity of the limestone rock acidic ocean water permeates upward. Groundwater salinity is also impacted by any salinity increase in rainfall. Sea spray collected on the vegetation and ground, mobilized by infiltrating water, is another source of salt that can be measured. Sea spray salt is deposited onto the land surface and infiltrates into the groundwater during subsequent rainfall events, whether through diffusion or direct flow. (Simard et al. 2015) found atmospheric deposition of chloride to be seasonally and spatially variable on the Northern Guam Plateau.

Another potential impact is dissolution of the limestone by freshwater that contributes to increase of calcium and magnesium content of Guam's groundwater, thus increasing its hardness. Seawater is about 1.3% magnesium ion and 0.42% calcium ion by weight. The hardness of untreated groundwater on Guam is between 172 and 610 ppm $CaCO_3$ (United States Environmental Protection Agency 2010) which rates as hard (172 ppm) to very hard (610 ppm) groundwater.

Sources of salt affecting Guam's groundwater salinity can include emitting more gases such as CO_2, agriculture, septic tank/leaching fields, water softeners, and leakage of chlorine-treated potable water from leaking transmission and distribution pipelines.

The density of freshwater is about 1,000 kilograms per cubic meter and the density of seawater is roughly 1,025 kilograms per cubic meter. This density difference, which is temperature dependent, leads to freshwater float on top of seawater. The static Ghyben-Herzberg principle suggests a density difference of 1140, for every unit of freshwater above sea level in an unconfined aquifer. There are 40 feet of freshwater in the usual water column below sea level. In the Ghyben-Herzberg equation (Equation 3.2) Pf is the density of freshwater; Ps is the density of seawater; h, hydraulic head is the elevation of freshwater above sea level, and z is the depth to the freshwater-saltwater interface.

$$z = \frac{\rho_f}{(\rho_s - \rho_f)} h$$

(Equation 3.2)

Throughout the NGLA, chloride concentrations are found to be more variable in recent decades compared to the 1970s (Simard et al. 2015). Chloride concentrations are higher during the 2000-10 decade than any of the previous decades in 112 of the 132 (84.8%) production wells with more than one decade of chloride data. Figures 3.1 and 3.2 below (Simard et al. 2015). compare increase in chloride levels in the same wells within a period of 1973~1979 (average levels are provided) to 2000~2010.

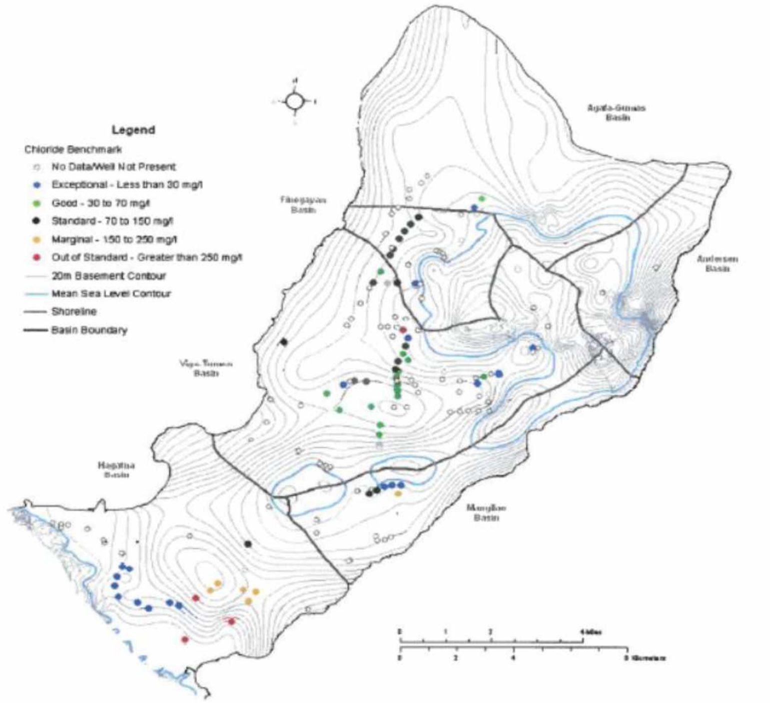

Figure 3.1 1973 to 1979 Mean Decadal Chloride Concentration in NGLA Production Wells Courtesy of Technical Report Number 143 titled "Salinity in the Northern Guam Lens Aquifer" by WERI, University of Guam

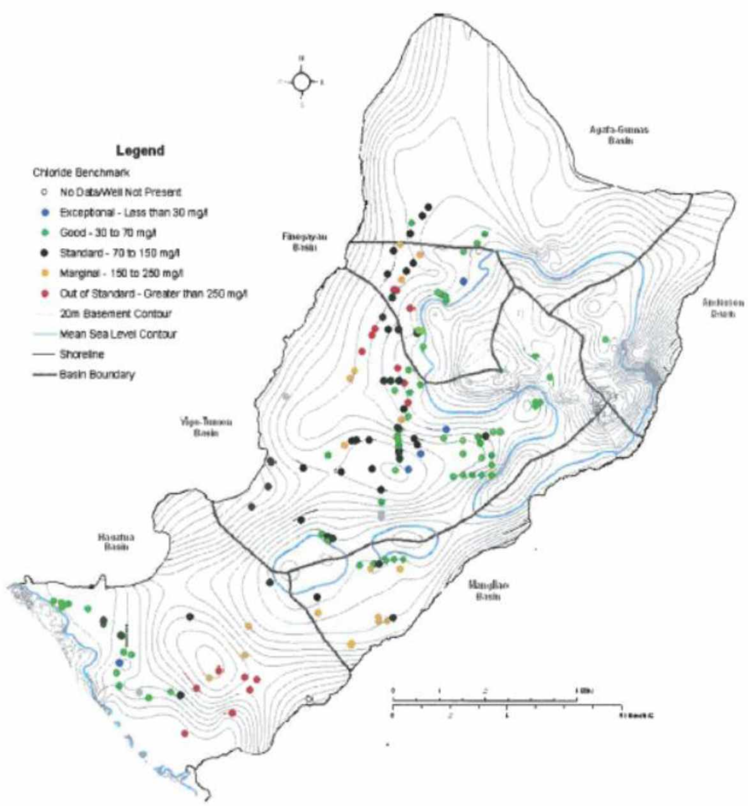

Figure 3.2 2000 to 2010 Mean Decadal Chloride Concentration in NGLA Production Wells Courtesy of Technical Report Number 143 titled "Salinity in the Northern Guam Lens Aquifer" by WERI, University of Guam

These data show that cyclical chloride trends, with varying periodicity, were observed at production wells in basal and para-basal groundwater zones. At many of those production wells, the magnitude of the chloride cycle also increases over time, which coincides with the increased variability exhibited in the last two decades (Simard et al. 2015).

The addition of more production wells combined with increasing pumping rates at many production wells in the past few decades may be causing increased mixing of variable density and variable salinity groundwater within the aquifer (Simard et al. 2015). Hydrologic factors may also be contributing to the increased variability, such as periods of below-average rainfall in conjunction with the increasing Mean Sea Level (MSL).

Table 3.1 Probable Causes of salinity Conditions 2000 to 2010 Courtesy of Technical Report Number 143 titled "Salinity in the Northern Guam Lens Aquifer" (WERI, University of Guam, 2015)

NGLA Production Well	2000-10 Mean Chloride Concentration (mg/l)	PROBABLE CAUSES OF SALINITY CONDITIONS							
		Termination depth exceeds NGLS guidelines	Excessive pumping (exceeds NGLS guidelines and/or permit rate)	Seasonal thinning of freshwater lens (Hagatna Argillaceous LS)	Upgradient well(s) reducing recharge	Proximity to saltwater toe	Proximity to coastline	Hydraulic connection to brackish water or seawater via fractures or conduits	Other / Non-seawater sources
A-9	214.7	x		x				x	x
A-10	341.7		x	x				x	x
A-13	424.5	x		x				x	x
A-14	309.6	x		x				x	x
A-15	162.6	x	x					x	x
A-17	437		x	x		x		x	x
A-18	362	x	x	x				x	x
A-19	400.9		x	x				x	x
A-21	400.4	x	x	x				x	x
A-28	175		x	x				x	x
D-8	283.7							x	x
D-9	180.4					x		x	x
D-13	518.1	x						x	x
D-17	171.2							x	x
D-26	256.8	x	x		x			x	x
F-4	192.7							x	x
F-6	359.9				x			x	x
F-10	291.9	x						x	x
F-11	174.4	x						x	x
F-13	260.6	x				x		x	x
F-19	251.9	x			x			x	x
F-20	278.8	x						x	x
H-1	173.6	x	x				n	x	x
HRP-1	164.6						n	x	x
HRP-2	198.8						n	x	x
M-1	162.8				x			x	x
M-9	171.6	x			x	x		x	x
MGC-1	202.1						n	x	x
MGC-2	213.2						n	x	x
NCS-A	285.1				x			x	x
NCS-2/2A	193.2	x	x					x	x
NCS-3/3A	182.2	x				x		x	x
NCS-5	164.9							x	x
NCS-10	177.8							x	x

The salinity of Guam's groundwater has increased for quite some time now. High pumping rates, increase in the number of wells drilled within a relatively close proximity, drilled production wells that are too deep and rise of sea level among others are definitely contributing to higher chloride levels observed in the groundwater.

3.4 Surface Water Turbidity and Concentration of Suspended Solids Specifically During a Heavy Precipitation Event Following a Dry Period

Recent surveys indicate that Guam's land cover and use changes have direct effect on water quality. Watershed water quality and the ecosystem are threatened constantly by both human impacts such as development and also natural phenomena such as storms and droughts. Therefore, it is critical to monitor land cover change in watersheds. The Ugum River and Fena Reservoir are the island's only supply of surface drinking water. For the Ugum River source, the turbidity of the raw water is extremely high during rainy seasons and the existing conventional treatment system cannot process the water to meet the Federal Environmental Protection Agency' Safe Drinking Water Act Standards (SDWA). Pre-sedimentation basins are needed to allow adequate settling to meet SDWA requirements. Increased monitoring is required due to the inability of the Ugum Water Treatment Plant to treat water meeting the turbidity standards during rain events. This turbidity issue, including proper disinfection, results in a degree of unreliability of clean water from this plant during the rainy season (August through October). The Fena Reservoir and its associated water treatment plant are more reliable but face similar monitoring concerns related to the turbidity and high suspended solids load during the rainy season.

3.5 Water Balance Estimates

Computations were made using data from the historical dry years for the projected future demands on the water infrastructure such as population increase impacts due to natural growth, tourism, and military relocation (Table 3.2).

As Guam's freshwater source is simply and solely due to precipitation, any impacts are related to the precipitation, for example, the ENSO relationship with the rainfall analyzed by using precipitation data from the historical dry years for Guam. For analysis purposes, Table 3.2 represents the recorded historical data of a single rainfall gage located at the airport for the relatively dry years during the past 70 years on Guam with the arbitrarily selected annual precipitation years below 70-inches. It can be argued that climate change impacts severity of the ENSO which in turn impacts the water security of Guam during dry years.

Table 3.2 Actual Monthly and Annual Total Rainfall for the Generally Low Precipitation Years (Below 70" Annually) Selected from NOAA Rainfall Data at the Guam International Airport

YEARS	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1959	2.42	1.31	1.47	2.61	0.83	1.2	5.02	12.57	15.67	8.36	6.4	3.76	61.62
1960	2.67	0.31	1.59	1.11	5.12	4.75	6.3	11.02	9.88	10.32	8.67	7.93	69.67
1966	1.92	1.12	1.2	0.51	1.36	5.18	5.18	13.65	20.71	6.53	8.47	3.68	69.51
1970	8.32	2.47	1.95	1.17	2.12	5.4	7.22	8.07	11.53	8.11	6.99	3.96	67.31
1973	1.15	1.71	0.89	1.09	1.65	3.57	6.04	9.5	8.08	15.55	2.73	7.18	59.14
1977	1.82	1.95	3.81	1.25	3.91	4.35	5.82	4.11	13.7	15.47	9.13	2.19	67.51
1983	0.95	0.61	2.73	0.53	2.01	0.83	7.21	13.56	10.05	7.95	10.14	4.48	61.05
1993	1.37	2.83	1.11	0.91	1.38	1.46	7.05	15.04	10.96	14.4	7.82	5.24	69.57
1998	1.99	1.22	0.97	1.51	1.05	4.52	5.38	4.44	16.44	9.64	6.78	3.94	57.88
AVERAGE	2.51	1.50	1.75	1.19	2.16	3.47	6.14	10.22	13.00	10.70	7.46	4.71	64.81
				Total Rainfall for Years of Low Precipitation (Below 70" Inches)									

The rainfall value related to 1998 (extremely low at 57.88”) was selected as an arbitrarily lower annual figure for the fresh water source when performing a water balance computation. However, in order to avoid extreme results while using a single year minimum rainfall of 57.88-inches (that occurred in 1998 El Nino year), the average of low annual rainfall years (less than 70”) during the past 70 years for Guam was computed from Table 3.2 as 64.81-inches. It is important to point out that the 64.81-inches figure compared with the overall seventy year plus annual rainfall average of 89.67-inches when years with no complete data were eliminated from the computation, represents a 27.7% reduction in annual rainfall. The water balance computations for the Southern parts of Guam are discussed next using Figure 3.3 and Table 3.3 followed by the Northern/Central parts of Guam using Figure 3.4 and Table 3.4.

The following water budget model is applied for the Southern Guam balance computations.

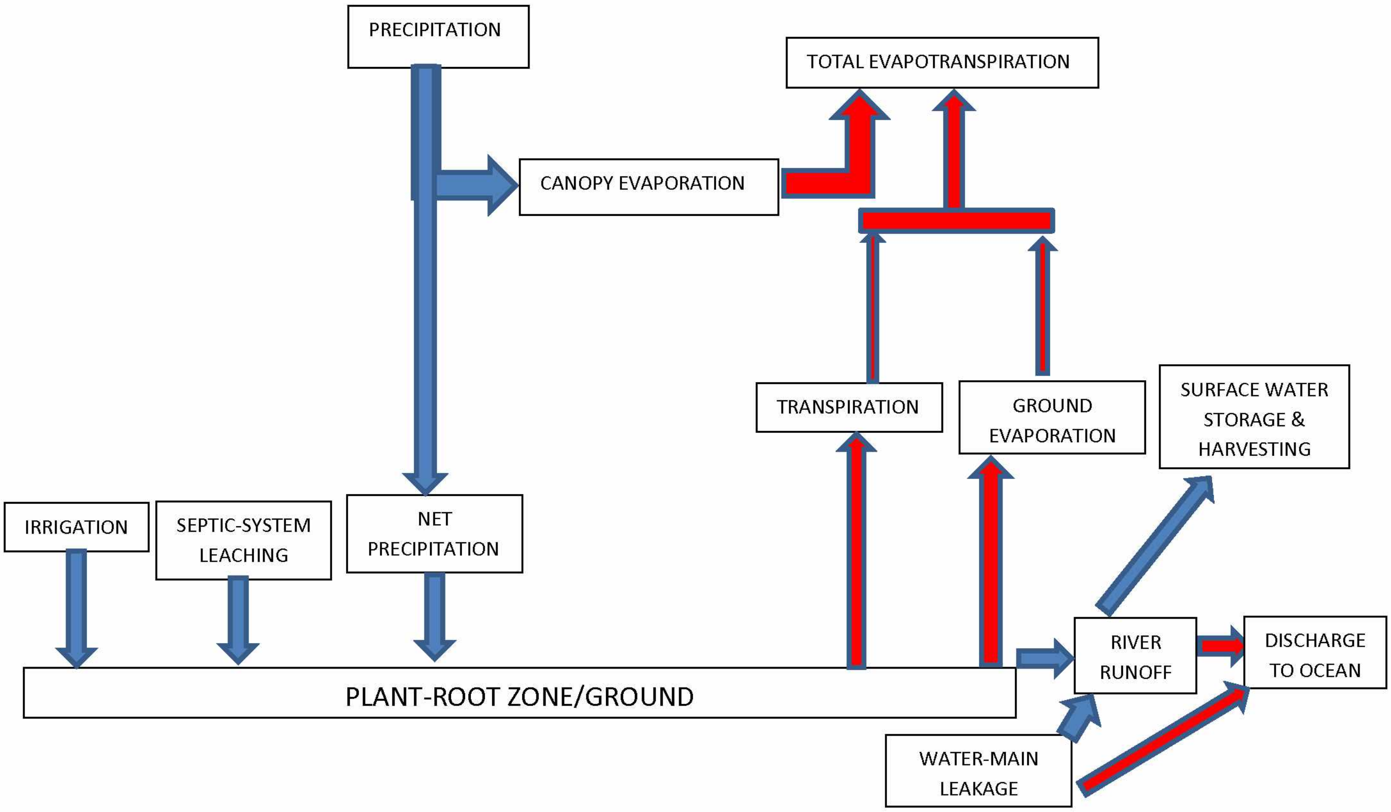

Figure 3.3 Southern Guam Surface water Budget Model

The Balance Equation P=R+ET is utilized for the above budget model
where:
P=Precipitation
R=Runoff that flows in rivers and streams (Southern Guam) or recharges the groundwater aquifer (Northern Guam), and
ET=Evapotranspiration

A conservatively high evapotranspiration rate of ET=42.79 inches per year as estimated for a higher annual rainfall has been utilized for this computation (Mink Technical Report # 1, September 1976, developed for an annual rainfall depth of 94.70")

Total watershed area (square miles) = 109.05

Annual ET (million gallons) = 81,098.76

Table 3.3 Estimated Water Balance/Demand Southern Guam during Average Dry Condition (64.81" Annual Rainfall)

		Watersheds (square miles) & Discharge Volume (million gallons, MG)														
	Rainfall	Agat	Apra	Cetti	Geus	Inarajan	Malojloj	Manell	Pago	Taelayag	Talofofo	Toguan	Ugum	Umatac	Ylig	TOTAL
Month	**(inch)**	4.36	13.65	3.07	1.73	8.55	8.56	4.55	10.35	3.22	22.37	1.41	7.31	3.84	16.08	**109.05**
January	2.51	190.20	595.46	133.92	75.47	372.98	373.42	198.49	451.50	140.47	975.86	61.51	318.89	167.51	701.47	4,757.14
February	1.5	113.66	355.85	80.03	45.10	222.90	223.16	118.62	269.82	83.94	583.18	36.76	190.57	100.11	419.20	2,842.91
March	1.75	132.61	415.16	93.37	52.62	260.05	260.35	138.39	314.79	97.94	680.38	42.88	222.33	116.79	489.07	3,316.73
April	1.19	90.17	282.31	63.49	35.78	176.83	177.04	94.10	214.06	66.60	462.66	29.16	151.19	79.42	332.57	2,255.38
May	2.16	163.68	512.43	115.25	64.95	320.97	321.35	170.81	388.54	120.88	839.78	52.93	274.42	144.16	603.65	4,093.79
June	3.47	262.94	823.21	185.15	104.33	515.63	516.24	274.40	624.19	194.19	1,349.09	85.03	440.85	231.58	969.75	6,576.60
July	6.14	465.27	1,456.62	327.61	184.61	912.39	913.46	485.54	1,104.47	343.61	2,387.15	150.46	780.07	409.78	1,715.93	11,636.98
August	10.22	774.43	2,424.54	545.30	307.29	1,518.67	1,520.45	808.18	1,838.39	571.94	3,973.41	250.45	1,298.42	682.07	2,856.16	19,369.70
September	13	985.09	3,084.06	693.63	390.87	1,931.77	1,934.03	1,028.02	2,338.46	727.52	5,054.24	318.57	1,651.61	867.60	3,633.09	24,638.56
October	10.7	810.81	2,538.42	570.91	321.72	1,590.00	1,591.86	846.14	1,924.73	598.81	4,160.03	262.21	1,359.40	714.10	2,990.31	20,279.43
November	7.46	565.29	1,769.77	398.04	224.30	1,108.54	1,109.84	589.92	1,341.92	417.49	2,900.35	182.81	947.77	497.87	2,084.83	14,138.74
December	4.71	356.91	1,117.38	251.31	141.62	699.90	700.71	372.46	847.24	263.59	1,831.19	115.42	598.39	314.34	1,316.29	8,926.74
	64.81															
Annual Volume																
Per Watershed (MG)		**4,911.05**	**15,375.21**	**3,458.01**	**1,948.65**	**9,630.62**	**9,641.89**	**5,125.07**	**11,658.12**	**3,626.97**	**25,197.31**	**1,588.21**	**8,233.90**	**4,325.33**	**18,112.33**	
Total Annual Gross Surface Water Discharge (million gallons)																**122,832.68**
Total Surface Water Storage from Fena Lake at 6 MGD (million gallons)																**2,190.00**
Total annual Evapotranspiration Volume (million gallons)																**81,098.80**
Total Estimated Annual Domestic Water Consumption for Areas not on Public Sewer (estimate 31,639 residents in 2017 at consumption rate of 125 gallons per person per day)																**1,443.53**
Total Annual Stored (surface storage), Lost (Evapotranspiration), and Consumed (million gallons)																**84,732.33**
Total Annual Net Surface water Discharge to the Ocean (million gallons)																**38,100.36**
Total Annual Freshwater Accessible during dry years from Surface Water Source (Ugum River at 1/4 runoff + Fena Lake) in million gallons																**4,248.48**
Total Daily Freshwater Accessible during dry years from Surface Water Source (Ugum River + Fena Lake) in million gallons																**11.6**
Assuming no significant industrial/agrictural demand utilizig existing infrastructure/access including approx. 60% Losses due to Pipe Leaks, (use rate = 125 gal/day/person can supply no. of people																**37,247**

The result of the computations provided in Table 3.3 indicates that for an average dry year rainfall depth of 64.81 inches a total 122,832.68 million gallons of runoff is expected. From this total runoff an annual approximate 4,248.48 million gallons is only harvested, treated, and used for Guam's freshwater system. This is done through Ugum River and Fena Lake sources. The balance of the total runoff (an approximate 118,000 million gallons) is lost through evapotranspiration, and direct discharge into the ocean via rivers and streams.

The above figures also indicate that considering the average total annual rainfall of 64.81 inches, there exists only a present water reserve for approximately an additional future population of 6,000 residents from the existing water supply system taking into account a 60% loss due to pipe leaks and illegal connections.

The following water budget model is applied for the Northern Guam balance computations.

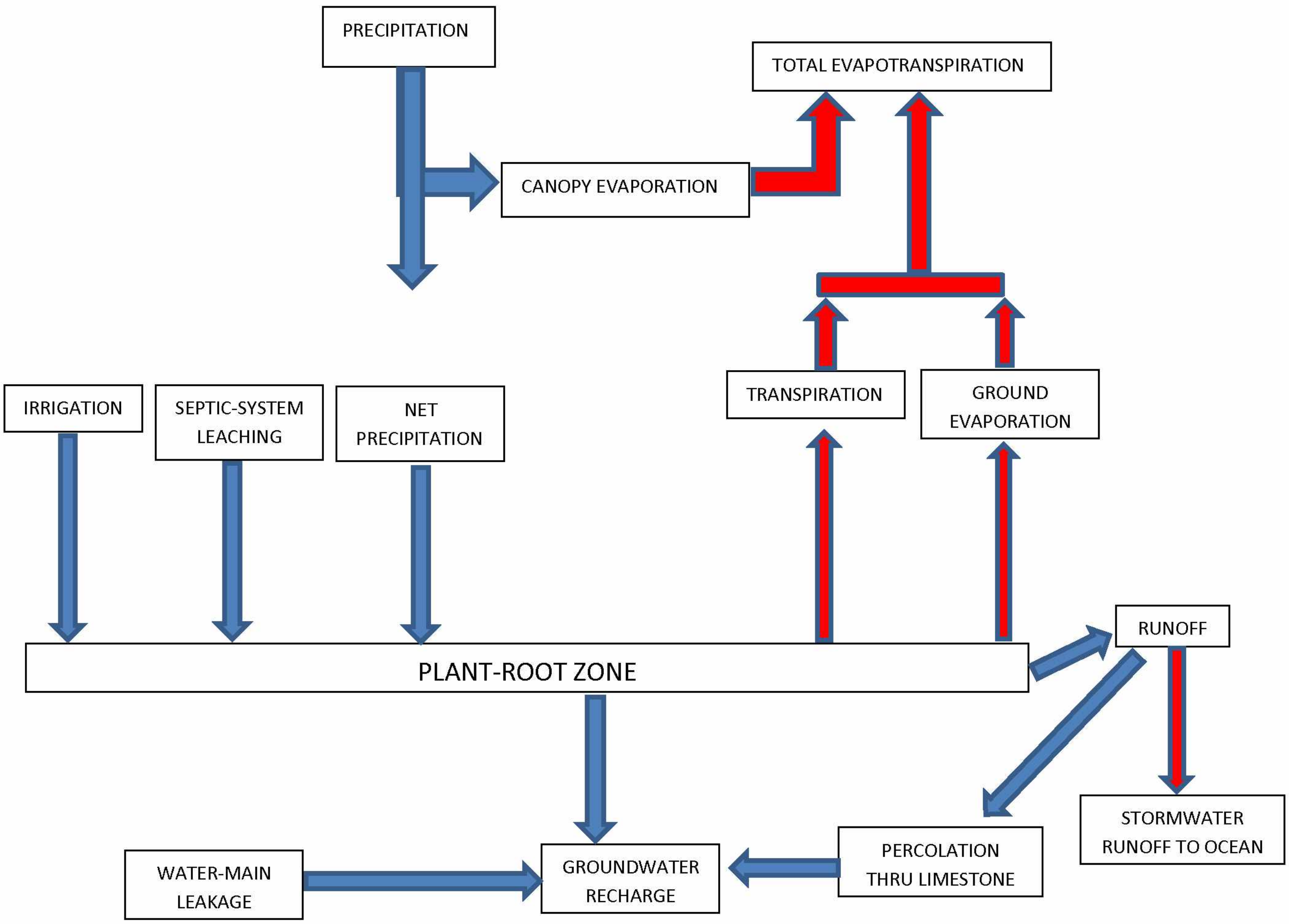

Figure 3.4 Guam Northern Groundwater Budget Model

The Balance Equation P=R+ET is utilized for the above budget model
where:
P=Precipitation
R=Runoff that flows in rivers and streams (Southern Guam) or recharges the groundwater aquifer (Northern Guam), and
ET=Evapotranspiration

Table 3.4 Estimated Water Balance/Demand, Northern & Central Guam during Average Dry Condition (64.81” Annual Rainfall)

Considering the geology of the Northern Guam the entire rainfall will infiltrate (percolate) through the highly fractured coraline limestone formation.		
Pan evaporation for Guam was measured to be 49.85" annaully from 1945~2005 at NAS Guam. Including a correction factor of 0.7 leads to 34.89"		
Therefore, the pan evaporation is assumed to be near zero. An annual transpiration figure of 7.90" is calculated by subtracting evaporation figure from the evapotranspiration of 42.79"-34.89" =7.90"		
The rainfall infiltration recharging the groundwater aquifer will therefore be similar to the total runoff computed for the southern half of Guam for the surface area of 212 -109.05=square miles	102.95	
Using the above computed Northern area of Guam the annual gross amount of rain infiltrating the limestone in million gallons will be.		115,961.71
Adjusted for the transpiration in (million gallons)		14,135.13
Adjusted for water consumption for the residents (100,000 approximately) served by public sewer system (irrigation is assumed to be neglegible) in mg		4,562.50
The net computed annual amount of rainfall recharging the groundwater lens for the Northern Guam is therefore equal to (million gallons)		97,264.09
Total daily water accessible during dry years from groundwater Source using existing pumping rates (appriximately 180 wells) in MGD		40
Daily available/accessable under present infrastructure condition at 60% losses MGD		16
Assuming no significant industrial/agricltural demand utilizig existing infrastructure/access including approx. 60% Losses due to Pipe Leaks, (use rate = 125 gal/day/person) can supply no. of people		128,000
Under present condition, Population of Northern/Central villages is 142,631 plus the bulk of 23,433 visitors that stay in this area at consumption rate of 125/day/person required demand MGD		20.76

The result of the computations provided in Table 3.4 indicates that for an average dry year rainfall depth of 64.81 inches a total 115,961.71million gallons of rainfall can be expected. From this total an annual approximate 14,400 million gallons is harvested and used for Guam’s freshwater system without much treatment other than chlorination. This is done through pumping approximately 180 production wells. The balance of the rainfall (an approximate 111,000 million gallons) is assumed to recharging the groundwater aquifer and be lost partially through evapotranspiration. Considering the above computation for the average dry year, while utilizing the existing piping infrastructure with an estimated 60% leak, there exists a freshwater supply deficit of approximately 4 to 5 million gallons per day.

3.6 Population and Water Quality Impacts

Based on the 2010 census Guam population was 159,358 and the Southern villages had a population of 29,027. Present population is estimated at 174,000. This represents a 9% percent increase since 2010 translating into 31,639 that is estimated to be the present population of Guam’s Southern villages.

Guam's visitor's arrival during the month of March 2017 was 140,662 (Guam's Visitor's Bureau). Based on the average 5 day stay per visit, this number translates into 703,310 person-days and an average sustained increase of 23,433 to the island population (an addition to the regular number of residents). Guam Visitor's Bureau is preparing for the arrival of 2 million visitors by the year 2020. This will translate into a population increase of 27,400.

It is also anticipated that potentially by the year 2020, an additional 15,000 military personnel, family members, support staff, and construction workers will enter Guam. Considering Guam's population (permanent residents only) for the year 2020, it is predicted to be 180,375. The total number of people on Guam at any given day by the year 2020 is then estimated at **222,775** (180,375+15,000+27,400).

The daily water demand (using 125 gallons per day per person as estimated by the Guam Waterworks Authority 2017) for the above population (year 2020) is estimated to be 27.85 million gallons per day (mgd). This figure does not take into account any industrial or agricultural demands. From the approximate 45 to 50 mgd freshwater presently harvested from groundwater and surface water sources on Guam, presently Guam Waterworks Authority's metering system registers an approximate average of 18 mgd.

The difference between harvest and meter measures is contributed to leaks and unauthorized connections. According to GWA's standards for daily water demand of 125 gallons per day (gpd), the 18 mgd figure that is presently being metered by GWA can only supplying a population of 144,000. The present population of 174,000 plus the tourism demand for an additional 23,000 people translate into a total population of 197,000 presently demanding municipal water on Guam. According to the above figures there is a shortage of water for **53,000** people on Guam (197,000-144,000 = 53,000).

Following the present standards of water use, there already exists a deficit in the quantity of the water supply based on the following factors: unauthorized connections, Guam residents utilizing less water than 125 gpd per person, people catching rain on rooftops and practically surviving off-grid, and the operating of private wells whether authorized or unauthorized.

In addition, as the quality of the water suffers due to increasingly higher levels of chlorides and suspended solids, the overall freshwater quantity can decrease. For example, looking at the Figure 3.2, in 2010 there existed 15 water production wells that exhibited unacceptable chloride levels of over 250 mg/liter. Assuming these wells yielded on an average 155 gallons per minute, this would have translated into approximately 0.23 mgd for each well and about 3.5 mgd as a total if pumped around the clock. This can be considered as a significant loss of freshwater back in 2010 (about 9%) and if the trend of chloride increase has continued at the same rate it did between years 1979 and 2010, then for 2017 the adverse impact is determined to be in the order of 24% loss of freshwater.

Chapter 4 Recommendations for Guam’s Freshwater Sustainability and Security

Given conclusions to the guiding research questions presented in this study, a new policy question arises, what are the essential components needed for Guam’s sustainability and security plan? This concluding chapter provides recommendations to address Guam’s freshwater sustainability and security. In summary, the guiding research questions were presented and addressed in the preceding chapters.

1. Is there evidence of climate change on the water security of Guam? Results hint at evidence of impacts of climate change presented in Chapter 2.
2. Could the global climate change impacts and local anthropogenic factors impact Guam’s water security? Guam could potentially be in peril based on the moderate climatic change and the increase in anthropogenic factors.

This chapter reviews historical data, future trends, and predictions from climate models to develop and make recommendation for a sustainable and secured water resources management plan for the island’s unique environment.

Recent climatological events frequently observed around the world points towards unique episodes that can no longer be classified as normal occurrences. It has been suggested that nature has been altered by anthropogenic activities and the impacts may not be easily reversed. The recent Hurricane Harvey is being used as an example of the impacts of global warming as relates to increasing air and sea surface water temperatures to development of prolonged storms impacting coastal environments. Simultaneously, rise of sea level has resulted in severe wave action surges during the storm events inundating the coastal communities.

Designing for the new wind loads should be an immediate priority with associated regulatory action. Recently suggested five-hundred-year or one-thousand-year rainfall events occurring at much higher intensities are considered as uncharted waters for the engineers and city planners. For example, civil engineering design manuals and building codes currently consider a one-hundred-year rainfall event (1% exceedance frequency) as the criterion for hydraulic design of roadways drainage structures. The design and building codes should now be revisited and revised accordingly, and as a precaution, include probability for potential impacts caused by more intense storms.

Major climatic changes related to wind and temperature increases, rainfall intensity, and sea level rise that are responsible for accelerated coastal erosion, saline intrusion into freshwater lenses, and increased flooding from the sea which impacts human settlements immensely are occurring. The following examples have been observed within the past 27 years on Guam.

- Disappearance of several small reef caps that were several inches higher than the water level during the high tides and now can barely be observed during the extremely low tides
- Ocean water encroaching into several beaches and threatening the coastal roadways
- Low duration rainfall events with extremely high intensity that causes overflow in the buildings' roof drainage systems

Sea level rise impacts the freshwater resource on Guam by shifting the saltwater/freshwater transition zone upward. Due to the inherent irregularity of the geology of the freshwater storing limestone formation of Guam, this shift does not impact the freshwater source at a linear one to one displacement (reduction) ratio. For example, a 6-inch rise in sea level does not reduce the freshwater lens thickness by 6-inches.

As the freshwater is pushed upward by the underlying sea water, freshwater quantity diminishes. The sea level rise will reduce the quantity and the quality of the groundwater. The surface water and river delta soil sediments are also impacted by the higher sea levels. The saltwater intrusion will reduce the quality of the river delta soil sediments by increasing the salt content, leading to a change in the ecosystem.

The present amount of water obtained from the ground and surface sources of Guam can satisfactorily meet the present and the short-term future (year 2020) population's demand provided that pipe leaks are repaired. A monitoring program for signs of degradation, the salinity, turbidity, and bacterial levels should be revitalized. Salinity and turbidity are indicators to augment current knowledge for planning and policy of source degradation in the quantity of the available freshwater. For example, water with chloride levels exceeding 250 mg/liter are not considered as potable (EPA Safe Drinking Water Act). As the island's water demands increase, if proper management practices are not developed and enforced, the effects of salinity will further diminish the quality of the available and accessible resource.

Guam's fresh water infrastructure presently suffers from inappropriate pumping rates, insufficient chlorination, inadequate storage capacities, and leaky transmission/distribution piping resulting in a tremendous loss of freshwater resources. This condition is further complicated due to inadequate preventive maintenance under Guam's highly corrosive air due to high humidity and salt ocean spray as well as frequent seismic events, and occasional typhoons. Repeated bacterial contamination in violation of the Clean Water Act and Safe Drinking Water Act are unfortunately occurring periodically as a result of operational, technical, and other related factors as reported by Federal EPA (Region IX) as far back as early 2000s.

Guam Waterworks Authority has from time to time violated regulatory limits for both coliform bacteria levels, turbidity levels, and seldom nitrate levels in the drinking water as reported in news releases posted in the local newspapers.

In light of the existing quality problems, the island of Guam needs a management plan to ensure adequate and sustainable access to freshwater in the future in light of the increase in temperature, increasing population, and infrastructure degradation. The following resource management recommendations and adaptation strategies are an outcome of this research and focus on sustainability and water security. Recommendations are open to interpretation. It is the hope of the researcher that the proposed management plan may be useful in developing a comprehensive water security policy plan for Guam.

4.1 Restoration of Existing Water Infrastructure and Related System Improvements

Leak detection, repair, or replacement of the existing water transmission and distribution pipes rank among the most immediate concerns. This item should first be addressed at the southern half of the island where the fresh surface water is supplied by streams and rivers. Leaks have been reported by GWA during the past several years throughout the island. Leaks associated with the freshwater transmission and distribution pipes in the southern region of the island will be lost via runoff to the ocean. Pipe leaks in the north-central region although problematic, will result in recharging the groundwater aquifer.

Repair or replacement of the existing freshwater storage tanks would increase water storage capacity. Corrosion protection of steel tanks and crack repairs related to the concrete tanks are considered a priority matter. Replacement of older tanks with new tanks might be less expensive in the long run than continuous repair of the older tanks.

Due to the improperly designed existing old transmission and distribution piping network, the system could benefit by replacement of its dilapidated asbestos pipes and installation of an adequate control system such as isolation valves, air relief valves, pressure relief valves and backflow preventers as required.

Improve water safety and quality by implementing a more reliable chlorination process that would protect against transport of bacteria and other contaminants into the freshwater piping and storage system. Chlorination systems should include a warning, alarm, and telemetry system to maintain functionality and reliability.

Recharge of the groundwater aquifer via properly designed and constructed percolation basins and injection wells within the north/central part of the island that can handle municipal storm runoff. The system should include regularly scheduled water sampling and testing to meet Guam Environmental Protection Agency water quality standards.

Perform sea-level rise and storm surge dynamic modelling and conduct extreme precipitation event modeling to better evaluate the risks and impacts on the surface and ground water resources. Use these results to determine the placement and protection of critical infrastructure. The process may lead to a potential relocation of utility infrastructure such as treatment plants, pump stations and troubled deep-water wells (exhibiting low yield or low quality) to higher elevations in order to reduce risks from coastal flooding due to storm surges and exposure as a result of coastal erosion. The process can also lead to a better watershed design and its management. Initiate the above research topics at the University of Guam WERI environmental science division for the growth of an emerging environmental management program.

As future electricity demand is forecasted to grow on Guam, localized energy shortages may occur. Therefore, development of "off-grid" sources such as solar and wind powered electrical generation can be a good strategy for electricity shortfalls. Moreover, a redundant power supply can provide resiliency for situations in which natural disasters cause power outages. On-site sources will complement the existing single source diesel power generation that is presently available on the island.

4.2 Groundwater Lens Aquifer Management Recommendations

The recommendations provided below are strategies to improve the understanding and management of the Northern Guam Lens Aquifer (NGLA) based on information compiled on the quality of water, in particular its chloride content.

All new production wells must maintain appropriate distance from septic tank/leaching fields and other similar means of domestic wastewater disposal. By implementing new capital improvement wastewater projects, the Guam Waterworks Authority must make a conscious effort towards eliminating the existing individual domestic wastewater systems (septic tank/leaching fields) that are presently located above the NGLA by connecting these units to the municipal wastewater system. The new wells should be drilled primarily in the para-basal zone and with appropriate distance from existing wells and each other.

Due to the rising sea levels, Guam's vertical datum was constructed as a fixed concrete platform several feet above the sea level (mean low water level). This new datum provides a fixed elevation benchmark for many years to come. Its designation includes GU for Guam, VD as vertical datum and the year as 2004 or 04 (GUVD04). Using this fixed datum is more accurate and will remove the need for the rising sea level that is no longer considered as a fixed datum. The wellhead elevations at all active production wells should be professionally surveyed to the Guam's new vertical datum of 2004 (GUVD04) in order to create an accurate NGLA groundwater contour map.

Pumping rates for wells should be evaluated and adjusted in the wells exhibiting higher levels of chlorides specifically at production wells situated in the supra-basal groundwater zone (see Figure 1.6).

Given the annual thinning of the freshwater layer during the dry season (January through June), and elevated chloride concentrations in some wells, adjustments to the pumping rates are highly recommended during the dry season. Also, during the dry seasons of the dry years (La Nino years), hydraulic head and drawdown measurements should be documented at all NGLA Production wells on a routine basis. Deep wells constantly exhibiting high chloride levels (250 mg/l and above) should be reconstructed with lesser depths based on established guidelines for well bottom depths.

Monitoring and analysis of anthropogenic sources of chloride is recommended, including industrial processes, agricultural processes, and chlorine-treated water leaks from the potable water supply distribution system. Eliminate the point-source storm runoff discharge as part of the road drainage system that presently collects, transmits, and disposes storm water directly into the ocean shallows. The runoff can alternatively be disposed of by properly designed and constructed percolation basins (with adequate geological thickness) in order to recharge the groundwater aquifer, especially along northern and central regions of the island.

4.3 Surface Water Management Recommendations

Following the results of the extreme precipitation event modeling, implement erosion and sediment transport control measures as required at the river tributaries leading to the Fena Lake and Ugum River among other watersheds. The control measures can lead to comprehensive watershed management to include security and erosion control that takes into account factors such topography, surface geology, soil erodibility and sediment transport. In addition, control microbial contamination of the surface runoff, caused by animals and human activities such as the environmentally damaging 4-wheel driving recreational activities.

Develop and implement additional watershed management tools to include securing the tributaries by installing enclosures where practical. Bacterial contamination can be further controlled by properly treating the surface water at the treatment plant including disinfection before transmission to the storage facilities.

General adaptive strategies related to the surface water management may include watershed management that entails a range of policy and technical measures. These measures should generally focus on preserving or restoring vegetated land cover in a watershed and managing storm water runoff. This can lead to improving the quality of runoff. In addition, planting hardy plants with deep root structure such as vetiver grass can enhance the deteriorated ground cover (badlands) related to the river tributaries. As fire frequency and severity may change in the future specially during the dry La Nino years, it is important to develop, practice and regularly update management plans to reduce fire risk. Farming practices that promote clearing and rejuvenating farmland by fire means should be discouraged. On the other hand, controlled burns, thinning, weed and invasive plant control programs can reduce risk in wildfire-prone areas.

4.4 Production of Freshwater Using Techniques New to Guam

Resilience can be augmented by increasing freshwater capacity. The following recommendations will increase freshwater reserves by capital investments.

Properly designed and maintained individual roof rainwater catchment and storage are a relatively low-cost technology that should be implemented in the southern villages where rainfall runoff flows to the ocean via the streams and rivers. The option of roof catchment is presently practiced throughout the Micronesia Islands.

Financial commitment by the government such as tax incentives relative to the initial cost and proper training for installation, storage, and disinfection are required by the Guam Waterworks Authority. The financial incentive and training would encourage the public to consider this option.

Reclaim, treat, and store storm water runoff from the Guam International Airport impervious surfaces such as paved aprons, taxiways, runways, and rooftops. Incorporate this great volume of freshwater into the islands potable water system. Presently this very large amount of water is being wasted by direct disposal via concrete open channels into the Harmon Sink that is a large limestone sinkhole located at the center of the island.

Consideration must be given to desalination technology utilizing solar or wind powers which are highly practical for the Guam environment. Producing freshwater from ocean water using reverse osmosis is a standard technology used around the world and by US Navy aircraft carriers.

Talofofo River, at a relatively high upstream elevation is among a few other possible surface water resources and may be suitable for a dam for increasing storage capacity and production of clean hydroelectric power. This option should only be considered if rigorous feasibility studies including environmental impact and economic assessments show positive results.

Guam is one of the few locations on earth that is ranked as “highly efficient” for application of the Ocean Thermal Energy Conversion Technology (OTEC) that produces clean electric power and high-quality water as a byproduct. In contrast to a dam, this can be achieved by applying the ocean water and its significant temperature differential (ΔT) at the surface versus the greater depth that is naturally available along Guam’s nearby eastern exposure.

As the Guam environment is quite humid, building interiors although well-insulated require dehumidification. Dehumidifiers and air conditioning systems as a byproduct produce a great volume of potable water during operation. If properly stored this high-quality water can be utilized.

4.5 Education through Conservation and Adaptation

An effective and low-cost method of meeting the increased water supply needs is to implement water conservation programs that will cut down on waste and inefficiencies. Public outreach is an essential component of any water conservation program. Outreach communications typically include basic information on household water usage, the best time of day to undertake water-intensive activities, and information on and access to water efficient household appliances.

As Guam educators have a tremendous opportunity to teach their students the significant role water security plays in our society, water education programs and the importance of water conservation should be conveyed to students. Especially the young students should learn and know where their water comes from and how it becomes the drinking water that pours out of a faucet. Also, a teacher should incorporate the idea of water conservation into his or her lessons. Lessons with specific tips on how a student can conserve water are particularly effective. For instance, simply turning off the water as they brush their teeth is a practical tip for both kids and adults that can save more than a gallon of fresh water per application.

Water pollution is a critical topic to include in an instruction unit on water. Students should learn the various causes of water pollution as well as the ways our environment is affected.

Instructors should teach students conservation and stewardship to create a sustainable Guam. The use of experiments and demonstrations are a good way to engage students. Young students are better able to retain the facts of a lesson if they are reinforced with a visual element.

The average American lifestyle demands 2,000 gallons a day for its support, with 70 percent of that going to support our diets. When it comes to conserving water, small adjustments can have a big impact. Water conservation techniques are numerous as shown in Table 4.1 below.

Table 4.1 General water conservation techniques applicable to the island of Guam

Choose outdoor landscaping appropriate for Guam. Native plants and grasses that thrive on natural rainfall only are best.
Agriculture represents the second largest user of water. In order to reduce agricultural water demand, utilities can work with farmers to adopt advanced micro-irrigation technology.
Install low-flow showerheads and faucet aerators.
Install low-volume, or dual-flush toilets.
Fix leaky faucets, toilet flush, and water leaks in general.
Run dishwasher and washing machine only when full. Use water- and energy-efficient models
Consider a diet rich on plant based foods and reduce the meat consumption. One typical hamburger approximately requires 630 gallons to produce. Drink more tea than coffee as coffee plants require greater amount of water for irrigation. Cut back on consuming rice and grains that require great amounts of water to grow.
Buy less stuff. Everything takes water to make. So if we buy less, we shrink our water footprint.
Recycle plastics, glass, metals, and paper. Buy re-usable products rather than throw-aways, as it takes water to make most everything.
Turn off the tap while brushing teeth and washing the dishes. Reduce a minute or two off your shower time. Millions of people are presently relying and surviving on a couple of gallons per day for all uses. Conserving even little amounts makes a great difference
In general conserve water and be mindful of the water rate (cost per 1000 gallon) is based on tier system that relates the monthly consumption to the overall cost on an increasing scale.

Chapter 5 Conclusion and Future Direction

The study answers both research questions reporting evidence of global climate change and local anthropogenic factors potentially impacting the water security of Guam. All climate change indicators except for the precipitation support the hypotheses that climate change trends are impacting Guam's water security. This will eventually weaken Guam's resilience. As a result, the urgency for developing public awareness and supporting policies for a sustainable water resource plan including adaptive strategies for the Island of Guam are recommended. Conservation through education appears to be an essential and integral part of these recommendations. This may include educational programs to enlighten both the public and the utility agencies. The education piece may lead to conservation/adaptation programs. The policy component can lead to capital improvement projects, operational, and maintenance program improvements.

Further research is required to study the impacts of increased water temperatures leading to eutrophication and excess algal growth that will reduce drinking water quality. The quality of drinking water sources will also be compromised by increased chloride levels, sediment or nutrient inputs due to extreme storm events that deserve further studies.

Further rigorous research on Guam's municipal water quality at the production wells, at the storage tanks, at the surface water reservoir, and rivers is recommended to test for several related parameters including chlorides, residual chlorine, bacteria, turbidity, and algal growth. The sampling should be performed seasonally (dry and wet seasons) for several years and its result should be matched with the rainfall measurements to search for potential trends.

In general, harsher environmental impacts predicted by increasing global warming trends as experienced on Guam will require additional research to evaluate the island's ever-changing water security requirements.

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